MINIMISATION OF TORQUE RIPPLE OF HYSTERESIS CURRENT CONTROLLED PMSM USING PI-RES CONTROLLER

A PROJECT REPORT

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Submitted by:

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CANDIDATE'S DECLARATION

I, Shilpa Ranjan, Roll No. 2K19/C&I/07 of M.Tech (Control & Instrumentation), hereby declare that the project Dissertation titled **" MINIMISATION OF TORQUE RIPPLE OF HYSTERESIS CURRENT CONTROLLED PMSM USING PI-RES CONTROLLER"** which is submitted by me to the Department of Electrical Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma, Associateship, Fellowship or other similar title or recognition.

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CERTIFICATE

This is to certify that the Project Dissertation titled **" MINIMISATION OF TORQUE RIPPLE OF HYSTERESIS CURRENT CONTROLLED PMSM USING PI-RES CONTROLLER"** which is submitted by Shilpa Ranjan, Roll No. 2K19/C&I/07 Electrical Engineering Department, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the student under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

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ABSTRACT

For the better dynamic performance of PMSM & minimum ripples in torque field oriented control (FOC) is implemented. Some intricate methods are applied for controlling & for the better performance of permanent magnet synchronous machine. For highly performed motor drives flux estimation is always important. The rotor flux estimation model is designed using high pass filter (HPF) to solve the problem caused due to integrator applied in the flux estimation. Also phase locked loop (PLL) is introduced in the model. It is known PMSM is used wherever smooth torque is required. But because of some application of power electronics devices in the modelling often reveals the cogging torque that led to ripple in torque. The key drawback of PMSM is that it produces ripples in the induced torque, which are undesirable in these high-performance applications. Torque ripples led to speed oscillations, which cause PMSM servo output to worsen. The ripples in torque produces mechanical vibrations and noise in the machine that decreases the life of machine. The smoothness of torque is considered as the essential requirement for high performance of permanent magnet synchronous motors. As a consequence, the primary issue in PMSM's control problem is ripple minimization. Since many torque ripples are caused by non-ideal back EMF in stators, a number of techniques for reducing ripples caused by this phenomenon have been developed. PI controllers are generally preferred but this got affected by the variations in parameters, load condition and also on speed. To overcome this problem, a resonant controller is introduced in accordance with PI for the minimization of ripples and to get the better performance. The performance of control methods of both PI & PI-RES controller is compared.

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LIST OF SYMBOLS & ABBREVIATIONS

P	No. of poles
B_m	Viscous damping
J	Inertia
ia,ib,ic	Three phase current
d	Direct axis
q	Quadrature axis
id	d-axis current
iq	q-axis current
Ld	d-axis inductance
Lq	q-axis inductance
Te	Electromagnetic torque
T_L	Load torque
λ	Flux linkage
ω^*	Reference speed
ω	Rotor speed
L_{dm}	d-axis magnetising inductance
θ	Rotor position
T_f	Time Constant
PM	Permanent Magnet
PMSM	Permanent magnet synchronous machine
BLDCM	Brushless DC machine

DC	Direct current
AC	Alternating current
VC	Vector control
FOC	Field oriented control
DTC	Direct torque control
EMF	Electromotive force
MMF	Magneto-motive force
HCC	Hysteresis current controller
PWM	Pulse width modulation
VSI	Voltage source inverter
CSI	Current source inverter
PLL	Phase locked loop
HPF	High Pass filter
LPF	Low Pass filter
CC	Current controller
PI	Proportional integral
RES	Resonant
PI-RES	Proportional integral-resonant
TRF	Torque ripple factor

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Motor drives are essential in a wide range of industrial applications, such as automotive, control applications, robotics, etc. It can be seen that in recent decades, progress in the development of electrical machines has generally been due to the technological advancement. Besides this, improvements in the production of materials used in their magnetic circuits, such as permanent magnet materials with high magnetic energy density and low-loss electrical sheets, or soft magnetic composites, have allowed electrical machines to perform at higher frequencies. On the other hand, major developments in methodologies and computer power have provided thorough analysis of electrical machines. The development of dc machines with PM field excitation in the 1950s was greatly enhanced by the ease of access to permanent magnets (PM) with high power density[1]. The inherent advantages of low rotor inertia, high efficiency, and high power density have attracted a lot of attention to permanent magnet synchronous machine (PMSM). PMSM eliminates the need for slip rings for field excitation, leading to lower rotor maintenance and losses.

With the characteristics of high torque at low speed, it has been commonly used. However, the key factor limiting the use of PMSM is torque ripple. Torque ripples should be minimized in applications that involve precise monitoring. A rotation coordinate system of the motor system is illustrated for torque ripple reduction. PMSM drives with vector control have a better dynamic response and less torque ripples. Different methods have been taken into consideration for the minimisation of ripples in torque of permanent magnet synchronous motor. The performance are implemented using MATLAB/Simulink software.

1.2 MATLAB/Simulink

MATLAB stands for MATrix LABoratory, and it is a computer programming language. MATLAB was developed to put things easy by using the LINPACK (linear system package) and EISPACK (Eigen system package) projects' matrix software. MATLAB is a high-performance technical computing language. It incorporates arithmetic, graphics, and a programming environment into one application. Furthermore, MATLAB(Fig.1.1) is a splitting programming environment. Since its initial release in 1984, the software package has been a standard tool in most colleges and enterprises across the world. It comes with a set of robust built-in algorithms that allow for a wide range of calculations. It also includes simple graphics commands that allow for quick depiction of results. The tools are grouped together in toolbox packages. Signal processing, symbolic computation, control theory, simulation, optimization, and a number of other disciplines of applied science and engineering all have toolboxes.

Simulink is a graphical extension of MATLAB that enables user to model and simulate systems. Simulink presents systems as block diagrams on the screen shown in Fig.1.2. Many block diagram elements, like as transfer functions, summing junctions, and virtual input and output devices including function generators and oscilloscopes, are available which is shown in Fig.1.3. These virtual devices will allow users to simulate the models you'll be creating. Simulink and MATLAB are tightly connected, and data may be easily shared between the both. We can use Simulink to apply to examples of modelled systems, then design controllers and simulate the systems.

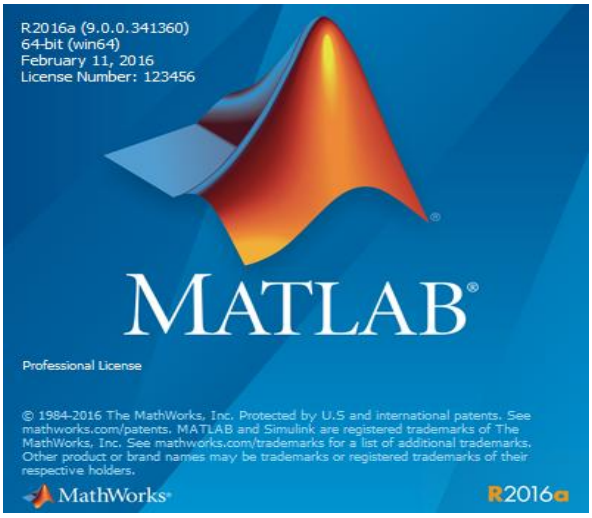


Fig.1.1 MATLAB software

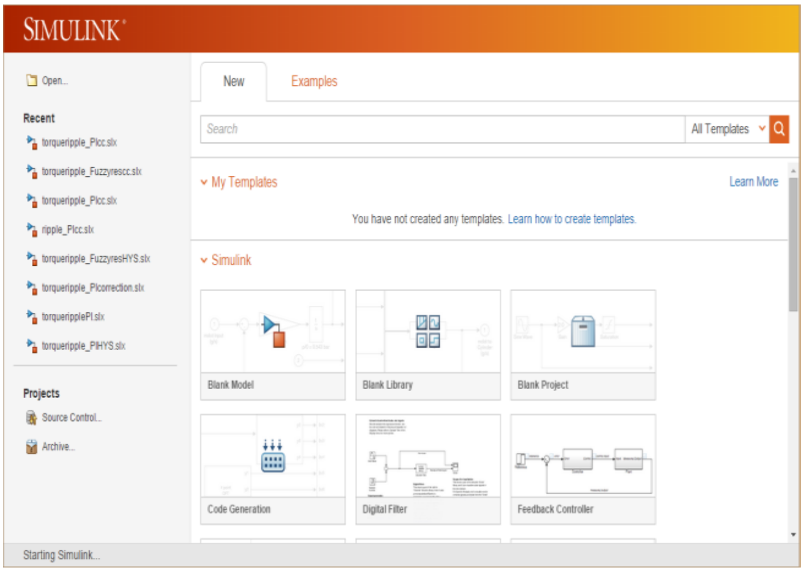


Fig. 1.2 Simulink page for implementation

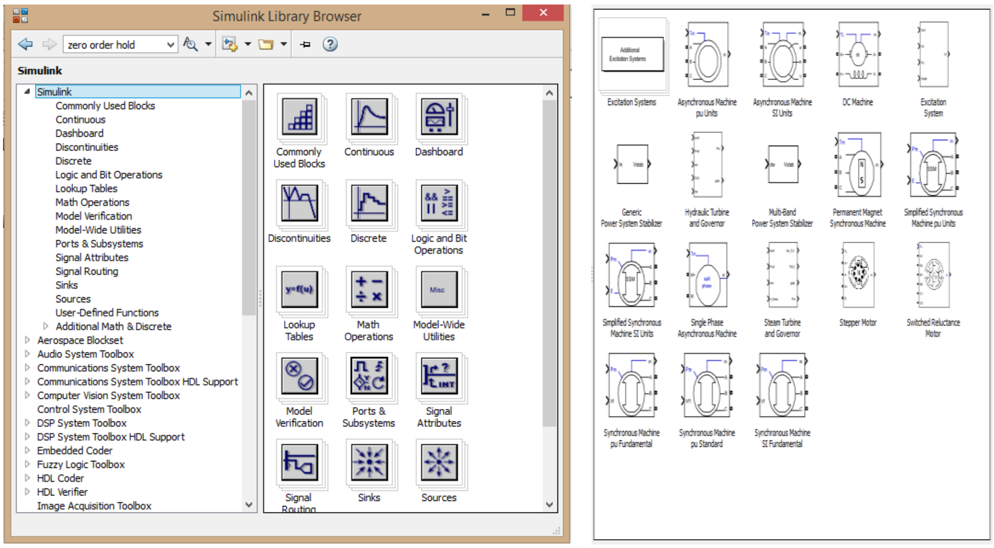


Fig.1.3 Simulink toolbox

1.3 MOTIVATION

The PMSM is widely utilised in robotics, machine tools, actuators, and high-power applications including industrial drives and automobile propulsion. It's also employed in both home and commercial settings. The demand for simulation tools capable of handling motor drive simulations has risen as the market for Permanent Magnet motor drives has increased. By lowering cost and time, simulations have enabled the growth of technological innovations, including motor drives. Because of the cost, modelling and simulation are often used in the design of PM drives rather than developing system prototypes. After all of the components have been chosen, the simulation procedure may begin to calculate the steady state and dynamic performance as well as losses that would have been achieved if the drive had been manufactured. Conventional PMSM control methods like vector control (VC) i.e. field oriented control (FOC), and direct torque control (DTC) are used to achieve good performance. But the only disadvantage of PMSM is ripples in torque while running at low speed. Several methods have been considered for minimisation of ripples in torque. PI-RES controller is one of the method employed for minimising ripples and to get better performance of PMSM.

1.4 RESEARCH OBJECTIVE

For a wide range of motion control applications, the permanent-magnet synchronous machine (PMSM) drive is one of the best choices. The modelling of permanent magnet synchronous motor is always vital for the proper simulation of drive.

- Field oriented control (FOC) is one of the control method which is employed to PMSM with hysteresis current controller (HCC) for better dynamic performance.
- The mathematical model of PMSM is derived in d-q reference frame and the performance of PMSM at different condition is implemented also the performance is observed after estimation of rotor flux using MATLAB/Simulink.
- PMSM is well known for producing high torque at low speed but this produces ripples in torque which causes major problems in the machine. So, to reduce the ripples induced in torque of PMSM, a resonant controller in parallel with PI controller is developed.
- The implementation result of performance of FOC of PMSM and the ripple minimisation in torque of PMSM which have been simulated is included in this thesis.

1.5 ORGANISATION OF THESIS

This thesis have been organised in six chapters.

In chapter 1, the brief introduction of PMSM and the software used for implementation has been described. This section also includes the motivation and research objective.

In chapter 2 , a literature review on the importance and control techniques of PMSM has been mentioned. The ripple minimisation review is also mentioned in this section.

In chapter 3, the description of PMSM drive system has been described which also consist of construction, working principle and current controllers used for PMSM.

In chapter 4, the modelling of PMSM has been discussed in which the simulink model of FOC of PMSM using HCC has been simulated and also through rotor flux estimation the observation results are shown. The simulated results has been included.

In chapter 5, Minimisation of ripples in torque of PMSM using PI and PI-RES controller has been carried out. It also consists of the calculation of ripples and the simulated results.

In chapter 6, the conclusion and future scope of the proposed controller has been described.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter deals with the previous work done. Simulink is used to develop a simulation of a field orientated controlled PM motor drive system. The simulation circuit will comprise all of the drive system's realistic components. This enables the estimation of currents and voltages in different aspects of the inverter and motor under different circumstances. In this chapter, the importance of PMSM drive system, the control techniques used for operating PMSM and the torque ripples are discussed.

2.2 IMPORTANCE OF PMSM DRIVE

For the past two decades, PM motor drives have been a major topic. Modelling and simulation of such drives has been done by a number of experts.

T. Sebastian, G. R. Slemon, and M. A. Rahman [2] investigated permanent magnet synchronous motor improvements in 1986, presented equivalent electric circuit models for such motors, and compared computed and observed parameters. The outcomes of lab motor experiments were also presented. In 1986, T.M. Jahns, G.B. Kliman, and T.W. Neumann [3], discussed that Interior permanent magnet synchronous motors (IPM) had specific characteristics for adjustable speed operation that distinguished them from other types of ac machines. They were rugged, high-density machines that could operate at high motor and inverter efficiency over a wide range of speeds, including a considerable amount of constant power operation. In 1988 Pillay and Krishnan, R.[4] presented PM motor drives and categorized them into two types: permanent magnet synchronous motor (PMSM) and brushless dc motor

(BLDCM) drives. To produce constant torque, the PMSM has a sinusoidal back EMF and requires sinusoidal stator currents, whereas the BLDCM has a trapezoidal back EMF and requires rectangular stator currents. The PMSM is analogous to a wound rotor synchronous machine, with the exception that the PMSM used for servo applications usually does not have any damper windings and excitation is produced by a permanent magnet rather than a field winding. As a result, the PMSM's d-q model may be obtained from the well-known synchronous machine model by eliminating the equations for damper windings and field current dynamics. As the motor is designed to operate under a field-oriented control (FOC) system, the damper windings are not taken into account. Because of the non-sinusoidal variation of the mutual inductances between the stator and rotor in the BLDCM, it is also demonstrated in this paper that converting the BLDCM's a-b-c equations to the d-q frame provides no measurable improvement. Pillay, P., and Krishnan, R. presented the permanent magnet synchronous motor (PMSM) in 1989 [5] as an extension of their prior work, which was one of several types of permanent magnet ac motor drives available in the drives industry. The flux distribution in the motor was sinusoidal. The use of vector control, as well as detailed modelling, simulation, and analysis of the drive system, were all highlighted. Real-time models of the inverter switches and vector controller, and also state space models of the motor and speed controller, were included. The wound rotor synchronous motor was used to develop the machine model for the PMSM. The equivalent circuit was provided without dampers and all equations were obtained in rotor reference frame. As the motor was developed to function in a drive system with field-oriented control, the damper windings were neglected.

Bose, B. K., in 2001[6], presented different types of synchronous motors and compared them to induction motors. The modelling of PM motor was derived from the model of salient pole synchronous motor. All of the equations were calculated in a synchronously rotating reference frame and represented as matrices. The permanent magnet was represented as a continuous current source in the analogous circuit, which had damper windings. The use of a voltage fed inverter for vector control was discussed.

Venkaterama, G. [7] had developed a simulation for permanent magnet motors using Matlab/simulink. The motor was a synchronous line start PM motor with a 5 hp output. Its mathematical model was derived in the rotor reference frame and incorporated the damper windings required to start the motor. Rotor currents, stator currents, speed, and torque plots were shown in the simulation. A three-phase motor rated 1.1 kW, 220 V, 3000 rpm was used in the simulink demo circuit (2005) for Permanent magnet synchronous motor fed by PWM inverter [8]. The PWM inverter was composed entirely from simulink blocks. Its output proceeded through Controlled Voltage Source blocks before accessing the stator windings of the PMSM block. There were two control loops involved. The stator currents of the motor were regulated by the inner loop. The motor's speed was controlled by the outer loop. The scope blocks' results included line-to-line voltages, three-phase currents, speed, and torque.

2.3 CONTROL TECHNIQUES OF PMSM

In a work published in 1994, Morimoto, S., Tong, Y., Takeda, Y., and Hirasa, T.[9] aims to improve efficiency in permanent magnet (PM) synchronous motor drives. The armature current vector could be ideally regulated to minimise the controllable electrical loss, which consists of copper and iron losses. The ideal current vector could be determined according to the operating speed and load conditions, and the control method for current vector minimising electrical loss was proposed. The developed control algorithm was tested on the experimental PM motor drive system, which used a single digital signal processor to perform the control algorithms and included various drive tests. Computer simulations and experimental results were used to investigate the operating characteristics regulated by the loss minimization control algorithm in sufficient complexity. The rotor position of PMSM is important for the vector control or FOC as they accomplish the position and velocity of PMSM rotor and the position of rotor can be achieved by using some sensors or encoders but it costs high. So, the rotor flux estimation model has been developed but the integrator used in the flux estimation model cause an offset error and this is the critical issue in the integrator operation for the rotor flux estimation and to solve the issue a low pass filter was introduced in the model but implementation was complicated [10].The different control techniques for PMSM is shown in fig.2.1

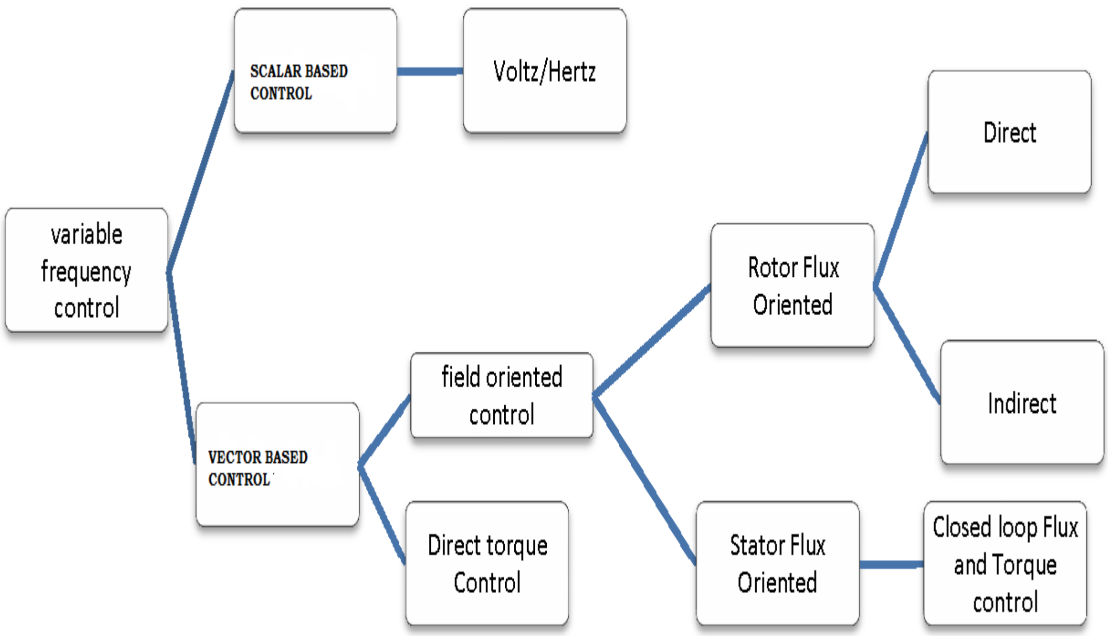


Fig.2.1 Control techniques for PMSM

The vector control of PMSM is based on the estimation of rotor flux. The stator current vector can be varied to control the torque of the PMSM. The PMSM attain the same satisfactory control performance as a DC motor while applying the vector control method. The vector control approach is commonly used for the high performance of ac drives. Some control techniques in detail is given below-

1. **Scalar Based Control**

The open loop scalar control technique, which is the most common control strategy for squirrel cage AC motors, is one of the method of controlling AC motors for variable speed applications. It is now designed for applications that do not require knowledge of the angular speed. It can be used in a wide range of drives since it ensures reliability at the expense of dynamic performance. Some low cost drives, Pump and fan drives, are some typical applications. The primary notion behind this method is that the supply voltage frequency is varied unexpectedly as a result of the shaft response. The speed dependency on the external load torque, particularly for PMSM, and the lower dynamic performances are significant disadvantages of scalar control method.

2. Vector Based control

The vector control of PMSM permits separate closed loop control of both the flux and torque, thereby achieving a similar control structure to that of a separately excited DC machine.

i. Direct Torque control (DTC)- For the control of an AC machine, the DTC is one of the high-performance control techniques. The selection of optimal inverter switching modes of operation controls flux linkage and electromagnetic torque directly and independently in DTC drive applications.

ii. Field oriented control (FOC)- The FOC methodology is used to evaluate synchronous motors as DC motors for the control of PM motors.

A great number of control approaches have been implemented in the control system. The task that is imposed in front of the electric drive determines whether control method is best. The primary approaches for regulating a PMSM in tabular form is shown in Fig.2.2

Control				Advantage	Disadvantage
SINUSOIDAL	Scalar			Control scheme is simple	Control is inefficient and ineffective for jobs with a changeable load and the possibility of losing control.
	vector control	FIELD ORIENTED CONTROL	With position sensor	Large control range, smooth and precise rotor position and motor rotation speed setting	Inside the control system, a rotor position sensor and a strong microprocessor are required.
			Without position sensor	There is no need for a rotor position sensor. Smooth and precise rotor position and motor rotation speed control, with a larger control range than a position sensor.	Only PMSMs with salient pole rotors can achieve sensorless FOC over the whole speed range, requiring the use of a strong control system.
		Direct torque control		Control circuit is simple, good dynamic performance, control range is wide and no rotor position sensor required	High torque and current ripple
TRPEZOIDAL	Open loop			Simple control scheme	Control is not optimal, not suitable for tasks where the variable load, loss of control is possible
	closed loop	With position sensor (Hall sensors)		Simple control scheme	Hall sensor required. Presence of torque ripple
		Without sensor		More powerful control system required	Not suitable for low speed operation. There are torque ripples

Fig. 2.2 Comparison of control techniques

2.4 RIPPLE MINIMISATION IN PMSM

The main reason for the existence of torque ripples in PMSM is due to non sinusoidal flux density distribution around the air gap and variable magnetic reluctance in the air gap due to stator slots. Torque smoothness is considered as the essential requirement in a wide range of high performance control applications.

In some applications low speed and high torque permanent magnet motors are used. The methods by which ripple in torque can be minimised are by machine design and some control techniques. Some design methodology have been yielded to minimise the throughout torque ripple. The design optimisation is inherent way to shorten the ripple in torque but machine design results into higher cost which is not feasible [11]. The permanent magnet torque ripple is regulated by the slot opening width and the permanent magnet width. Depending on the number of slots per pole / phase, the torque ripple tends to be the minimal for one or two different permanent magnet widths. The third harmonics of air gap flux density are reduced using this method [12]. To reduce the ripples, several controllers were implemented. One of the controllers is sliding-mode control, which is based on a generic mathematical model of the motor. The estimation is based on the robust exact differentiator's (RED) principles for differentiating measured signals . On an industrial servo drive, this method is implemented [13]. To suppress harmonics, torque ripples, noise, and electromagnetic interference, the preferred approach uses two PI controllers. The frequency of invert switching is affected by PI controllers, which lowers the cogging torque. Because of the smooth waveform of current and torque, PMSM provides smooth operation [14]. Electrical energy is often used as a source of energy in the number of research. However, this approach is based on fuel cells as a source of energy. Torque ripple is reduced when a fuel cell feeds a boost converter, which then feeds a three phase tri-state CSI, as illustrated in a Hybrid Electric Vehicle [15]. To decrease torque ripple, the Direct Torque Control (DTC) algorithm is used. In a PMSM, the angle between the stator and rotor flux is proportional to the electromagnetic torque. The fundamental advantage of Direct Torque Control (DTC) is its design simplicity, which gives superior dynamic performance. An improved PMSM DTC system based on an RMS torque-ripple equation reduction and an active null vector modulation technique. By combining low torque ripple characteristics in steady state with greater torque dynamics, the proposed methodology increases DTC performance [16]. Cogging torque in permanent magnet motors can be lowered by using the tooth shape optimization method. Starting with three fundamental shapes, the implemented algorithms developed an optimal tooth shape [17]. The repetitive current controller combined with PI controller so that the output that is controlled tracks the set of reference inputs but this control implementation leads to instability because of the presence of higher order harmonics [18]. For the minimisation of ripple in torque, iterative learning control with different laws were proposed & then implemented in time and frequency domain. The IL controller was used in parallel with PI controller for the compensation of reference current & this gives simple implementation and reduced torque ripple. But there was requirement of electrical torque as feedback from transducer & that increase the cost of machine [19].

2.5 CONCLUSION

In this chapter the discussion about previous work done is illustrated where it is seen that PMSM has the advantage of high power density and high torque at low speed and because of these advantages they are used in many industrial applications. The PMSM simulink model was also developed to ease the implementation. The only disadvantage i.e. ripples in torque of PMSM due to running at low speed is the main issue. There were several methods implemented to minimise the ripples but all those methods consist of some limitations because of design technique of PMSM, optimisation in parameters, use of PI controller and so on. So, a high pass filter(HPF) is acquainted in the model to address the offset error while estimating rotor flux and for minimisation of ripples in torque the resonant controller in parallel with the PI controller proposed for the better performance and minimum ripple in torque of permanent magnet synchronous machine while implementation.

CHAPTER 3

DESCRIPTION OF PMSM DRIVE SYSTEM

3.1 INTRODUCTION

This chapter describes the description of permanent magnet synchronous machine in which construction of PMSM, classification of PMSM on various aspects and also the working principle of PMSM is described. The details of permanent magnet is also reviewed in this chapter. The current control techniques of PMSM is also studied and finally the conclusion is mentioned.

The permanent magnet (PM) motor, inverter, control unit and the position sensor are the four main component of motor drive system. The components are arranged as shown in Fig.3.1

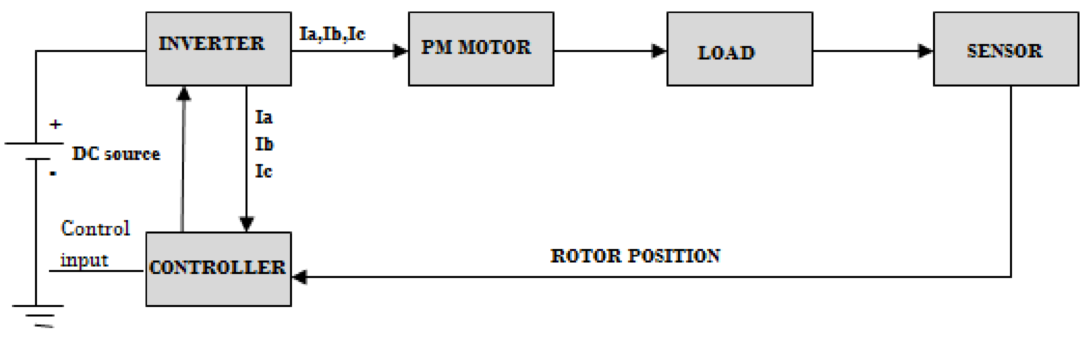


Fig.3.1 Schematic of drive system

3.2 PERMANENT MAGNET SYNCHRONOUS MOTOR

The permanent magnet synchronous motor is a type of synchronous motor which utilise permanent magnet for the production of the excitation field. This type of motor is also known as the brushless permanent sine wave motor. The different parts of PMSM is shown in Fig.3.2. It gets its name from the sine-shaped flux distribution it produces in the air gap between the stator and the rotor. It also possesses a current waveform that appears as a sine wave. A permanent-magnet AC (PMAC) machine, or simply called as PM machine, is another term for the PMSM. A permanent magnet synchronous motor (PMSM) is a motor that generates the air gap magnetic field utilizing permanent magnets rather than electromagnets. These motors have a number of benefits that have attracted the interest of researchers and industry for usage in a wide range of applications. It's sometimes called a brushless DC (BDC) machine because, with the right control, it may approximate the input/output characteristics of a separately excited brush-type DC machine [20].

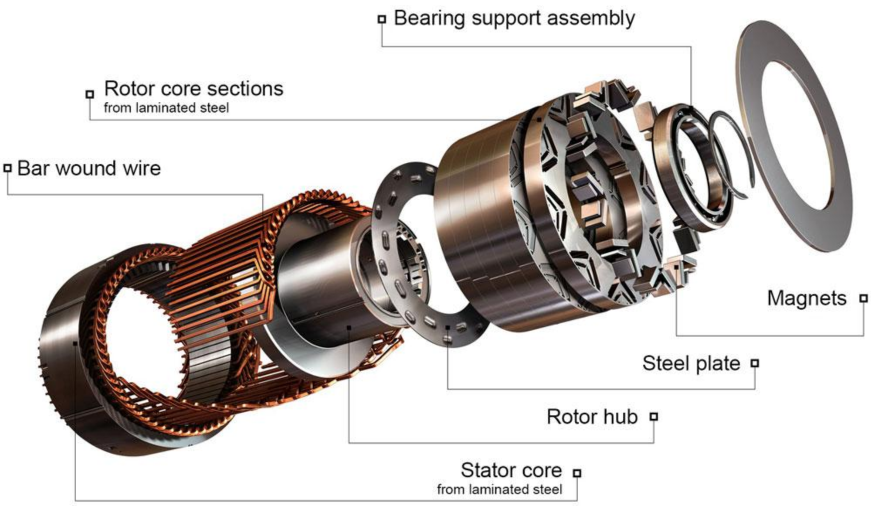


Fig.3.2 Parts of PMSM

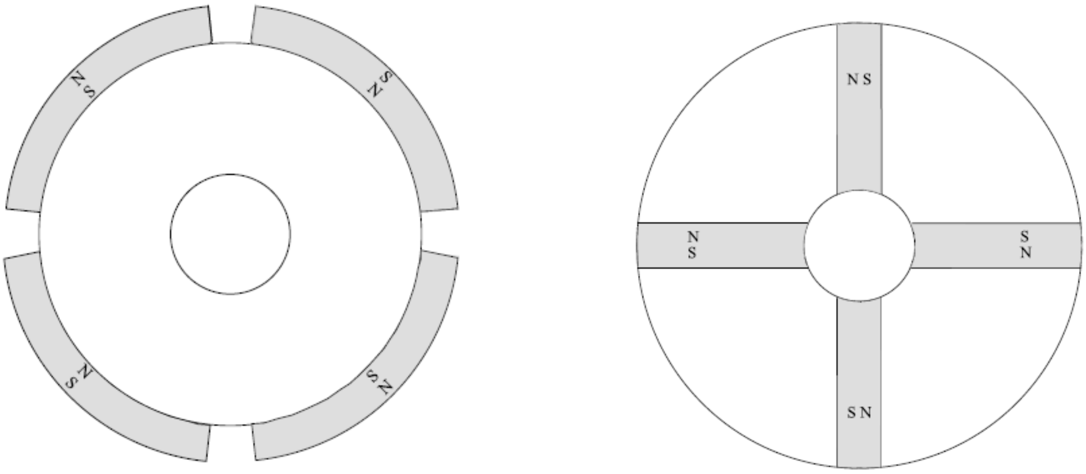
3.2.1 Permanent magnet materials

Permanent magnets are made of ferromagnetic materials like iron, nickel, and cobalt, as well as rare-earth metal alloys and minerals as lodestone. Permanent magnets, unlike electromagnets, produce a magnetic field that lasts without the use of any external magnetism or electrical power. The permanent magnet material's characteristics will have a direct impact on the motor's performance, hence adequate knowledge is essential for material selection and understanding PM motors. Hardened steel was the first magnet material to be manufactured. Steel magnets were very easy to magnetise. However, they could only hold a very small amount of energy and were easily demagnetized. Other permanent magnet materials, such as Aluminium Nickel and Cobalt Alloys (ALNICO), Strontium Ferrite or Barium Ferrite (Ferrite), Samarium Cobalt (First Generation Rare Earth Magnet) (SmCo), and Neodymium Iron-Boron (Second Generation Rare Earth Magnet) (NdFeB), have recently been introduced and used and these are shown in Fig.3.3.

Fig. 3.3 Different permanent magnets

3.2.2 Construction of PMSM

The PMSM is made up of a multiphase stator and a rotor with permanent magnets, as previously described. Flux might be oriented radially or axially in the machines. Fig.3.4 shows some popular radial-flux rotor configurations. The magnets can be mounted on the rotor surface or buried in the rotor iron shown in Fig.3.4(a & b). As the stator inductance is essentially independent of rotor position, the surface-mounted type is popular due to its ease of manufacturing and control, and also the virtual absence of reluctance torque. Due to position-variant stator inductance, the interior magnet variety of rotors has considerable reluctance torque, which complicates analysis and control problems. The magnetic saliency, on either side, can be advantageous for operating above base speed. There are some other stator design modifications available, particularly in terms of slot skewing and tooth form. There are many different motor designs, each with its own set of performance and cost constraints. The choice of magnets and other design elements are essential. Ferrite is a prime source that is affordable and has a low magnetic strength. Rare earth magnets such as neodymium-iron-boron (NdFeB) and samarium-cobalt (SmCo) are magnetically stronger and more temperature resistant. Ferrite magnets are commonly used in low-performance motors. Depending on the application, both radial and parallel magnetization are commonly deployed.



(a) (b)

Fig.3.4 (a)Surface mounted PMSM (b) Interior PMSM

3.3 CLASSIFICATION OF PMSM

Permanent magnet synchronous machines (PMSMs) are classified on various aspects.

- On the basis of direction of field flux

  i. Radial field flux
  ii. Axial field flux

The radial field motor is the first field flux classification, having flux propagating along the radius of the motor. The second type is an axial field motor, in which the flux is perpendicular to the motor's radius. Axial field flux has become a major topic and is implemented in a few applications, while radial field flux is most typically utilised in motors.

- On the basis of flux density distribution

The flux density distribution and the pattern of current excitation are being used to categorize PM motors. PMSM and PM brushless motors are the two different types of motor. The back EMF of the PMSM is sinusoidal in shape, and it is designed to generate sinusoidal back EMF waveforms. They consist of the following:

1. In the air gap, the magnet flux is distributed in a sinusoidal manner.

2. Current waveforms with Sinusoidal form.

3. The stator conductors are distributed in a sinusoidal pattern.

The back EMF of the BLDC is trapezoidal in shape, and it is intended to generate trapezoidal back EMF waveforms. They consist of the following:

1. In the air gap, the magnet flux is distributed in a rectangular pattern.

2. Current waveform with a rectangular shape.

3. Windings in the stator are concentrated.

- On the basis of design of rotor

  i. Surface permanent magnet synchronous motor (SPMSM)
  ii. Interior permanent magnet synchronous motor (IPMSM)

i. SPMSM

A surface mounted permanent magnet rotor is used in surface mounted PM motors, as seen in Fig.3.5. Each PM is located on the rotor's surface, making it simple to assemble, and particularly skewed poles can be magnetised easily on this surface mounted type to reduce cogging torque. As the magnets will fly apart during high-speed operations, this design is only employed for low-speed applications. These motors are said to have a low saliency, which means they have practically identical inductances in both axes. Because the permanent magnet's permeability is nearly equal to that of air, the magnetic material extends the reach of the air gap .

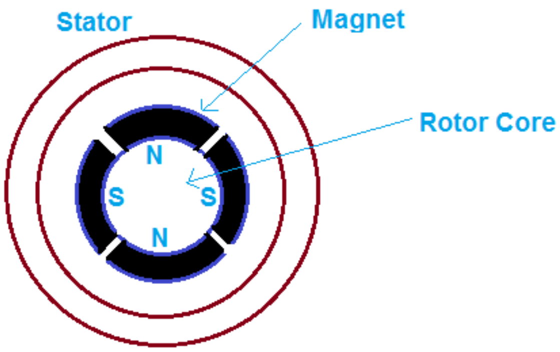


Fig.3.5 Surface mounted PMSM

ii. IPMSM

Interior or buried PM motors have internal mounted permanent magnet rotor as shown in Fig.3.6. The permanent magnets are mounted into the rotor instead of surface. Although it is not as popular as the surface-mounted variety, it is an excellent choice for high-speed operation. With a q axis inductance greater than the d axis inductance ($L_q > L_d$), these motors are regarded salient. Due to presence of saliency, reluctance torque is there in IPMSM.

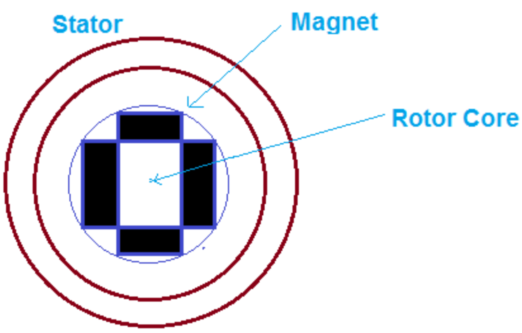


Fig.3.6 Interior PMSM

3.4 WORKING PRINCIPLE OF PMSM

In comparison to traditional motors, the permanent magnet synchronous motor's operation is relatively simple, quick, and efficient. The stator's revolving magnetic field and the rotor's constant magnetic field are both required for PMSM to function. Permanent magnets act as the rotor, producing a steady magnetic flux that operates and locks at synchronous speeds. The phasor groups are defined by putting the stator's windings together. These phasor groups are connected to produce different connections, such as a star, Delta, double, and single phase. The windings should be wound close together to reduce harmonic voltages. When a 3-phase AC supply is applied to the stator, it produces a rotating magnetic field, while the permanent magnet of the rotor induces a constant magnetic field. This rotor rotates at the same period as the synchronous speed. With no load, the whole operation of the PMSM is dependent on the air gap between the stator and rotor. The motor's windage losses will be reduced if the air gap is large enough. The permanent magnet's field poles are very important. Motors with permanent magnets are not self-starting. As a result, electronically controlling the stator's variable frequency is required.

3.5 CURRENT CONTROL

Control techniques for the AC machine currents are used in high-performance drives to generate command signals. Because an AC current regulator must manage both the amplitude and phase of the stator current, AC current regulators are difficult to design. The inner loop of the overall motion controller is the AC drive current regulator**.** Controlled current modes are available for both current source inverters (CSI) and voltage source inverters (VSI). The current source inverter is a "natural" current source that can easily be converted to controlled current. When compared to the CSI, the voltage source inverter requires more complexity in the current regulator but provides considerably better bandwidth and eliminates current harmonics. It is almost solely utilised for motion control applications. Hysteresis and PWM current controllers are the two types of current controllers.

3.5.1 PWM controller

Current controllers with pulse width modulation (PWM) are commonly utilised. In most cases, the switching frequency is kept constant. They work on the principle of comparing a triangular carrier wave with a specified switching frequency to the error of a regulated signal. The error signal is the result of combining the controller's reference signal with the negative of the actual motor current. The comparison will generate a voltage control signal, which will be sent to the gates of the voltage source inverter, causing the desired output to be generated. Its control react according to the error. The inverter leg is held switched to the positive polarity if the error command is greater than the triangle waveform (upper switch on). This will produce a PWM signal similar to Fig.3.7. The inverter leg is switched to negative polarity when the error signal is less than the triangle waveform (lower switch on). The inverter leg is driven to switch at the triangle wave's frequency, resulting in an output voltage corresponding to the current error command. The controlled output current is a repetition of the reference current with high-frequency PWM ripple imposed on it [21].

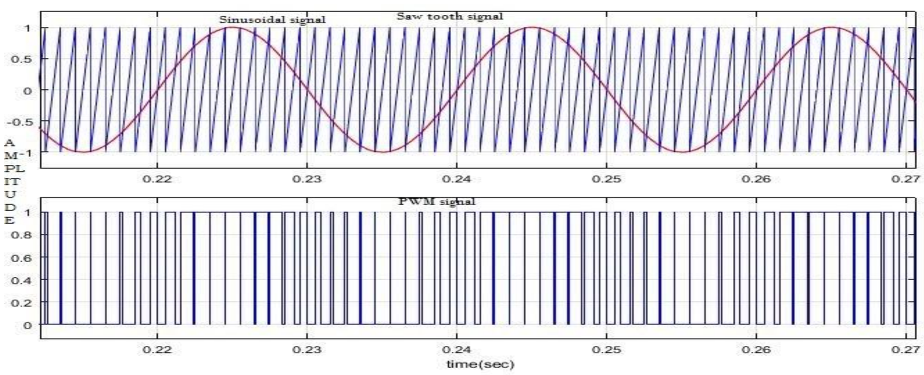


Fig. 3.7 PWM current control

3.5.2 Hysteresis current controller

Inverter currents can also be controlled with a hysteresis current controller. Hysteresis current controller (HCC) because of its simple implementation, fast response and accurate results are widely used. For production of reference current it is considered as the most appropriate pulse width modulation switching methods. As we know for speed control of motor current control method are applied in most of the ac drives having high performance. The HCC switches the inverter that is voltage source(VSI) so the stator current of motor tracks the set reference current responses[22].Some of the characteristics of hysteresis current controller are precise and fast dynamic response, also the stability of HCC is considered high. The current control loop having large bandwidth(BW) that results in the precise current tracking is used in the high performance vector controlled(VC) drives.

Hysteresis Band Technique: The hysteresis band control technique requires to define upper and lower limit of hysteresis band. The hysteresis band method shows the comparison between the current applied and the limit of band given to it. The performance is observed as when the current passes the upper band limit , the switches gets OFF and when it passes the lower band limit , the switches gets ON. HCC generates the reference current by means of the inverter and that in the range marked by thickness of the hysteresis band gap. It is seen that the error between desired current (i_{abc}^*) and the measured current (i_{abc}) is given to the comparator holding hysteresis band[23] The hysteresis band is used for controlling the current of VSI. The conventional method & the model of hysteresis controller in simulink is shown in Fig^s.3.8 & 3.9.

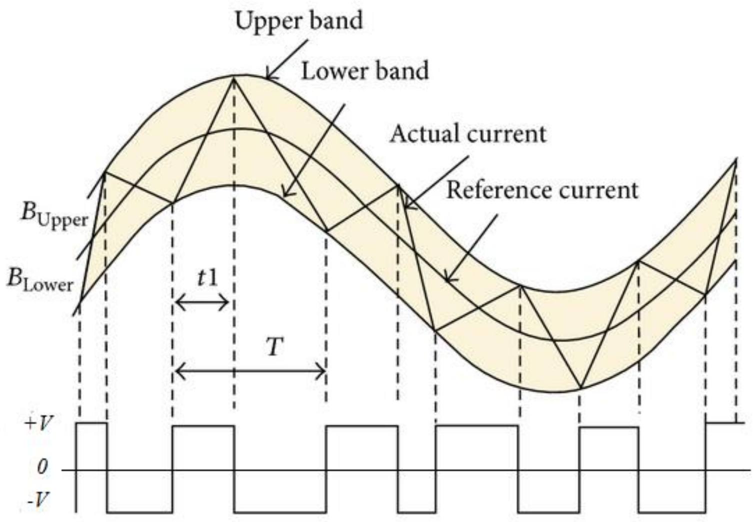


Fig. 3.8 Two level Hysteresis current controller

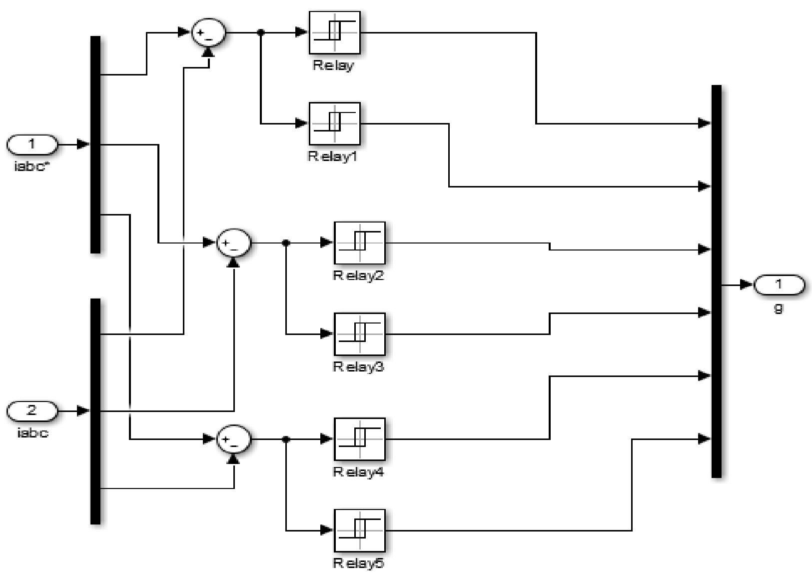


Fig. 3.9 Simulink model of Hysteresis current controller

3.6 CONCLUSION

In this chapter description of PM synchronous machine in which construction of PMSM, classification of PMSM on various aspects and also the working principle of

PMSM is described. The classification of PMSM is done on various aspects and with all these details the advantages of permanent magnet synchronous machine and its applications is known. The different current control methods discussed and the idea of hysteresis current controller (HCC) technique is described.

CHAPTER 4

MODELLING OF PMSM

4.1 INTRODUCTION

This chapter describes with the dynamic modelling of permanent magnet synchronous machine, its control technique i.e. FOC , the transformation of co-ordinates and the principle of rotor flux estimation. It also consists of block diagrams, simulink models and different simulation results of the implementation. And also the conclusion is included.

4.2 DYNAMIC MODELLING OF PMSM

The modelling of permanent magnet synchronous motor is always vital for the proper simulation of drive. To derive the effective model of PMSM, the stator equation of induction machine in the reference rotor frame considering flux linkage is taken. Some assumptions are taken for PMSM modelling and these are:

i. Sinusoidal induced EMF.
ii. Negligible eddy and hysteresis losses.
iii. No dynamics of field current.
iv. Saturation is neglected

The equivalent circuits shown in Fig.4.1 of the motors are used for study and simulation of motors as it is essential for the proper simulation and designing of the motor. The equivalent circuit is shown without dampers, and the PMSM equations are determined in rotor reference frame. The equivalent circuit of the motor can be determined from the d-q modelling of the motor using the stator voltage equations. . In Fig.4.2. considering rotor reference frame, a d-q model of PMSM has been developed[20]. The rotor d axis flux is assumed to be represented by a constant current source, which is given by the equation given below-

$$\lambda_{af} = L_{dm} I_f \qquad 4.1$$

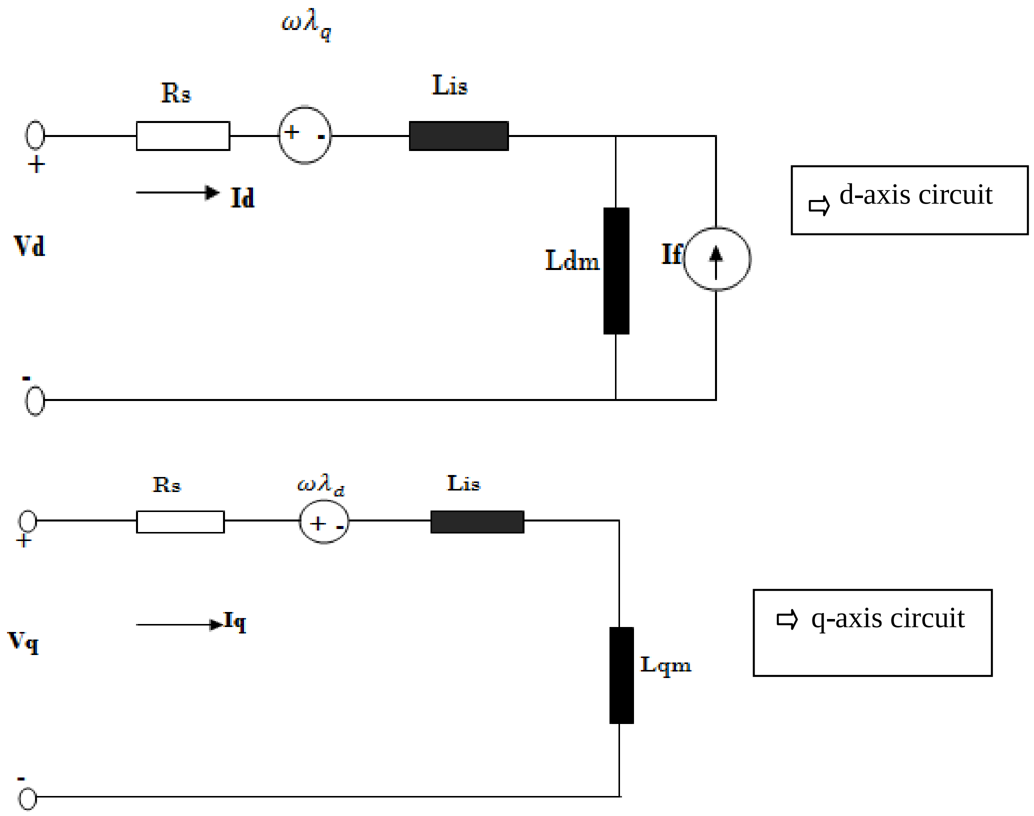


Fig.4.1 PM motor equivalent electric circuit without damper windings

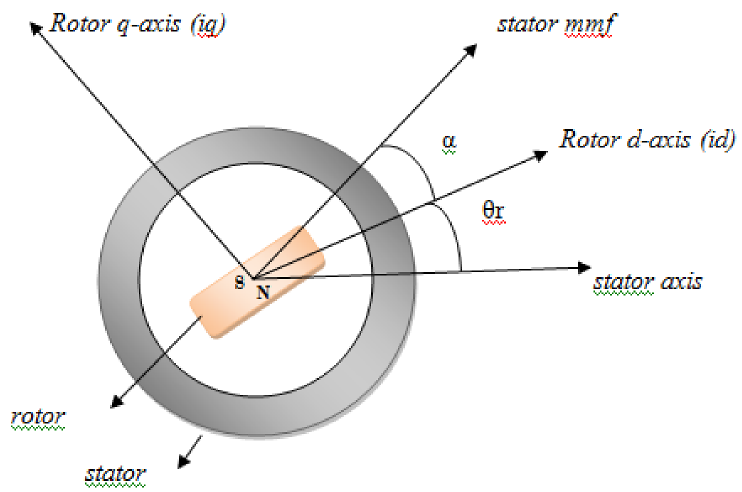


Fig.4.2 PM synchronous motor d-q axis

The representation of α-β and d-q components of PMSM is shown in Fig. 4.3.

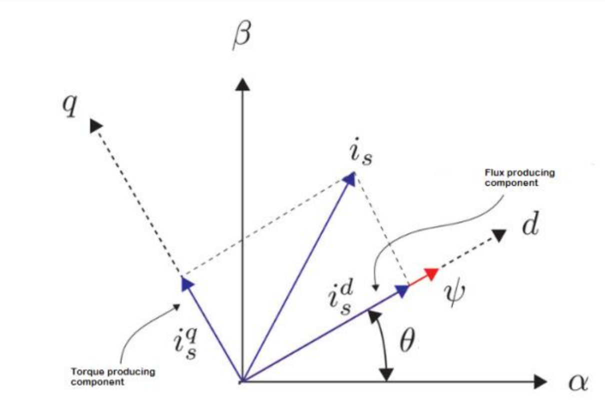


Fig.4.3 Components of α-β and d-q

Taking all these assumptions into consideration, the PMSM voltage equation in rotor reference frame are:

$$V_q = R_s i_q + \omega_r \lambda_d + \rho \lambda_q \quad 4.2$$

$$V_d = R_s i_d - \omega_r \lambda_q + \rho \lambda_d \quad 4.3$$

and the flux linkage is given by-

$$\lambda_q = L_q i_q \quad 4.4$$

$$\lambda_d = L_d i_d + \lambda_{af} \quad 4.5$$

where, V_q& V_d are the stator voltages of q & d axis. i_q, the stator current of quadrature axis & i_d, the stator currents of direct axis. L_q, the inductance of q-axis and L_d is the inductance of d-axis. λ_{af} represents the flux linkage of stator due to PM. R_s is the stator winding resistance per phase and ω_r is the rotor speed of motor in radian per sec. Substituting equations (4.2.4) & (4.2.5) in eq^n. (4.2.2) & (4.2.3) and rearranging them in matrix form we get;

$$\begin{bmatrix} V_q \\ V_d \end{bmatrix} = \begin{bmatrix} R_s + \rho L_q & \omega_r L_d \\ -\omega_r L_q & R_s + \rho L_d \end{bmatrix} \begin{bmatrix} i_q \\ i_d \end{bmatrix} = \begin{bmatrix} \omega_r \lambda_{af} \\ \rho \lambda_{af} \end{bmatrix} \quad 4.6$$

The electromagnetic motor torque produced is specified as

$$T_e = \frac{3}{2} P \left\{ \lambda_{af} i_q + \left(L_d - L_q\right) i_d i_q \right\} \quad 4.7$$

where , P shows the no. of pole pairs.

The relationship between electromagnetic torque and load torque expressed as

$$T_L = T_e - J \frac{d}{dt} \omega_r - B\omega_r \quad 4.8$$

& the mechanical speed of rotor is given by

$$\omega_r = \frac{1}{J} \int (T_e - T_L - B\omega_r) dt \quad 4.9$$

The equation of voltage in α-β axis of PMSM is :

$$V_{s\alpha} = i_{s\alpha} R_s + \frac{d}{dt} \psi_{s\alpha} \quad 4.10$$

$$V_{s\beta} = i_{s\beta} R_s + \frac{d}{dt} \psi_{s\beta} \quad 4.11$$

where,

$$\psi_{s\alpha} = i_{s\alpha} L_s + \psi_{f\alpha} \quad 4.12$$

$$\psi_{s\beta} = i_{s\beta} L_s + \psi_{f\beta} \quad 4.13$$

where, $V_{s\alpha}$& $V_{s\beta}$ denotes stator voltage . $V_{s\alpha}$ & $V_{s\beta}$denotes stator flux, $\psi_{f\alpha}$ & $\psi_{f\beta}$ denotes rotor flux, $i_{s\alpha}$ & $i_{s\beta}$ denotes stator current. R_s & L_s denotes stator resistance and inductance. The simulation of model is performed on 3Φ, 1.1kW motor and the parameters listed in Table 1.

Table.1 PM synchronous motor parameters

Power, P_{in}	1.1 kW
Rated Voltage & current	400V, 3.75A
Rated torque, T	3.5 Nm
Speed, N	3000 rpm
Poles, P	4
Stator resistance, R_s	0.3Ω
Flux linkage, λ_{af}	0.185Wb
Inductance of q-axis, L_q	0.0085H
Inductance of d-axis, L_d	0.0085H
Inertia, J	0.0027kgm^2

4.3 FIELD ORIENTED CONTROL

To control PM synchronous motor , a number of complex control idea needs to be applied. FOC is the method in which it separates the 3ph stator current into 2ph rotating (d-q) axis current. These 2-Φ direct & quadrature axis current consist of flux component and torque component. And these components approves the direct control of flux and torque. It is also considered that by applying FOC, the PM synchronous machine is the same as to separately excited DC machine. The derived model of PMSM is non-linear & by applying FOC the model of PMSM becomes linear. The notion of field oriented control is based on the transformation of co-ordinates and also on the torque equation of motor by controlling stator current for the enhancement of performance of motor. The approach of FOC is predicated on the synchronized rotating frame of reference. The methods that is applicable for the transformation of co-ordinates are park transformation & clarke transformation [24]. The PM synchronous motors are designed in such a way that the magnet of rotor itself is capable for the production of necessary air-gap flux upto the rated speed. Therefore, id is considered zero in the constant torque mode operation. The 3-Φ currents considered as-

$$i_a = I_m \sin(\omega t + \alpha) \quad 4.14$$

$$i_b = I_m \sin\left(\omega t + \alpha - \frac{2\pi}{3}\right) \quad 4.15$$

$$i_c = I_m \sin\left(\omega t + \alpha + \frac{2\pi}{3}\right) \quad 4.16$$

The components in phasor diagram shown in Fig. 4.4., the component that produces torque is the d-axis current represented as i_d and the component that produces flux is the q-axis current represented as i_q & if the direct axis current i.e. i_d equals to zero when α =0 is considered, then the equation of torque becomes

$$T_e = \frac{3}{2}\frac{P}{2}\lambda_{af} i_q \quad 4.17$$

Therefore, it is seen that the electromagnetic torque of PMSM relys on the current of q-axis (i_q) only and it is ensured that the current of d-axis (i_d) is fixed. The uniform air-gap flux of PMSM is essential upto rated speed.

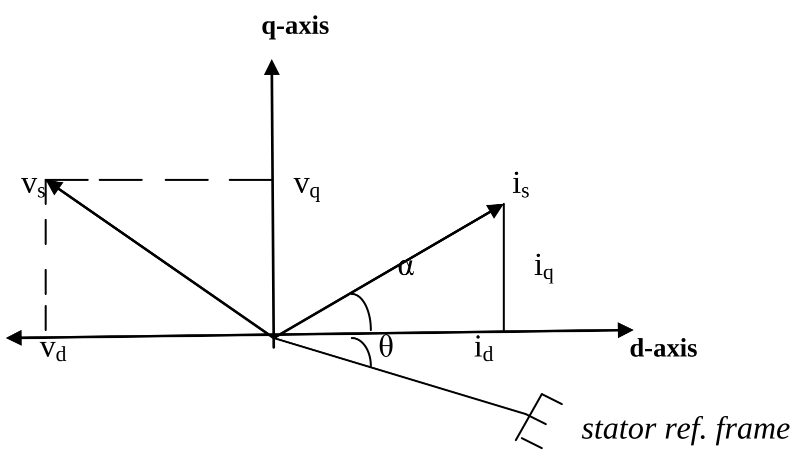


Fig. 4.4 Phasor diagram of PMSM

4.3.1 CLARKE TRANSFORMATION:

In this transformation, the 3-Φ reference current of stator transfigured to the α-β orthogonal reference frame that is stationary. The mathematical expression for the 3-Φ to 2-Φ orthogonal system is given as:

$$i_\alpha = \frac{2}{3} i_a - \frac{1}{3}(i_b - i_c) \qquad 4.18$$

$$i_\beta = \frac{2}{\sqrt{3}}(i_b - i_c) \qquad 4.19$$

where, i_α& $i_\beta$are the component of 2-Φ orthogonal reference frame and the 3-Φ stator current denoted by i_a,i_b & i_c .

4.3.2 PARK TRANSFORMATION

In this transformation, the 2-Φ stationary reference frame transforms to the 2-Φ rotating frame of reference. The α-β quantities obtained from the Clarke transformation is supplied to the vector rotating block for the rotation at an angle theta to track the rotating reference frame associated to the rotor flux.

$$i_d = i_\alpha \cos\theta + i_\beta \sin\theta \qquad 4.20$$

$$i_q = -i_\alpha \sin\theta + i_\beta \cos\theta \qquad 4.21$$

id & iq are the current of reference frame that is rotating and iα & iβ are the components of orthogonal fixed reference frame. θ is the angle of rotation for transformation done. The frame of reference for the transformation done is shown in Fig. 4.5.

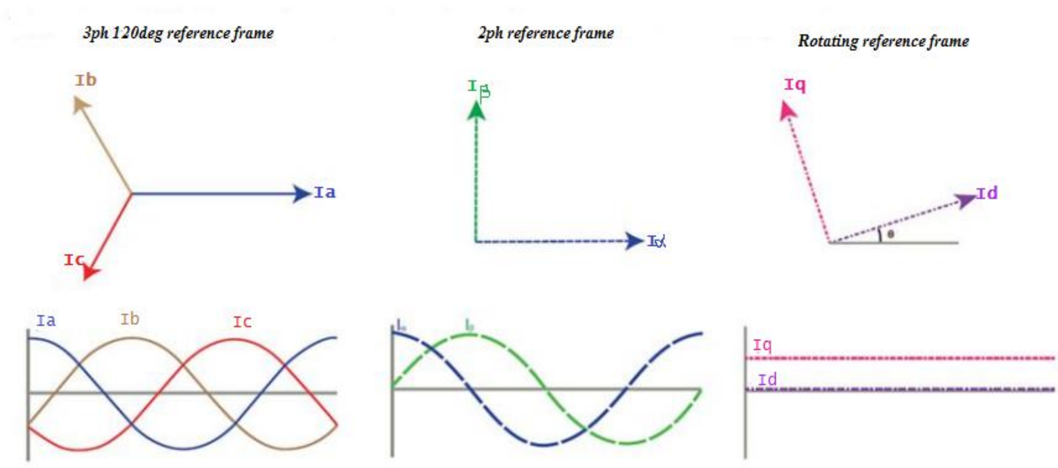


Fig. 4.5 Co-ordinate transformation

The expression carried out for the transformation of dq-abc is given as:

$$i_a = i_q \cos\theta - i_d \sin\theta \qquad 4.22$$

$$i_b = i_q \cos\left(\theta - \frac{2\pi}{3}\right) - i_d \sin\left(\theta - \frac{2\pi}{3}\right) \qquad 4.23$$

$$i_c = i_q \cos\left(\theta + \frac{2\pi}{3}\right) - i_d \sin\left(\theta + \frac{2\pi}{3}\right) \qquad 4.24$$

The modelling of dq-abc transformation is done using simulink and the model is given in Fig. 4.6.

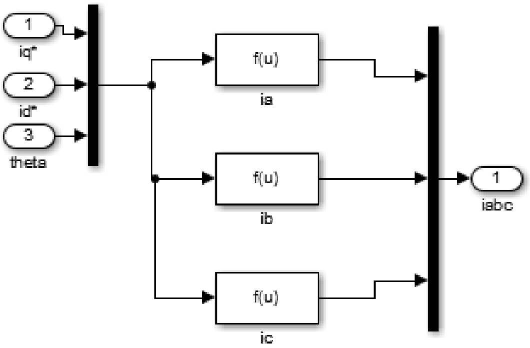


Fig. 4.6 Simulink model of d-q to abc transformation

The FOC block diagram using HCC is given in Fig. 4.7. In this block diagram there are two closed loops i.e. outer & inner loop where speed loop is the outer and current loop is the inner loop. The direct axis (d-axis) & the quadrature axis (q-axis) are separated and the PI controller is applied for the performance of pmsm.

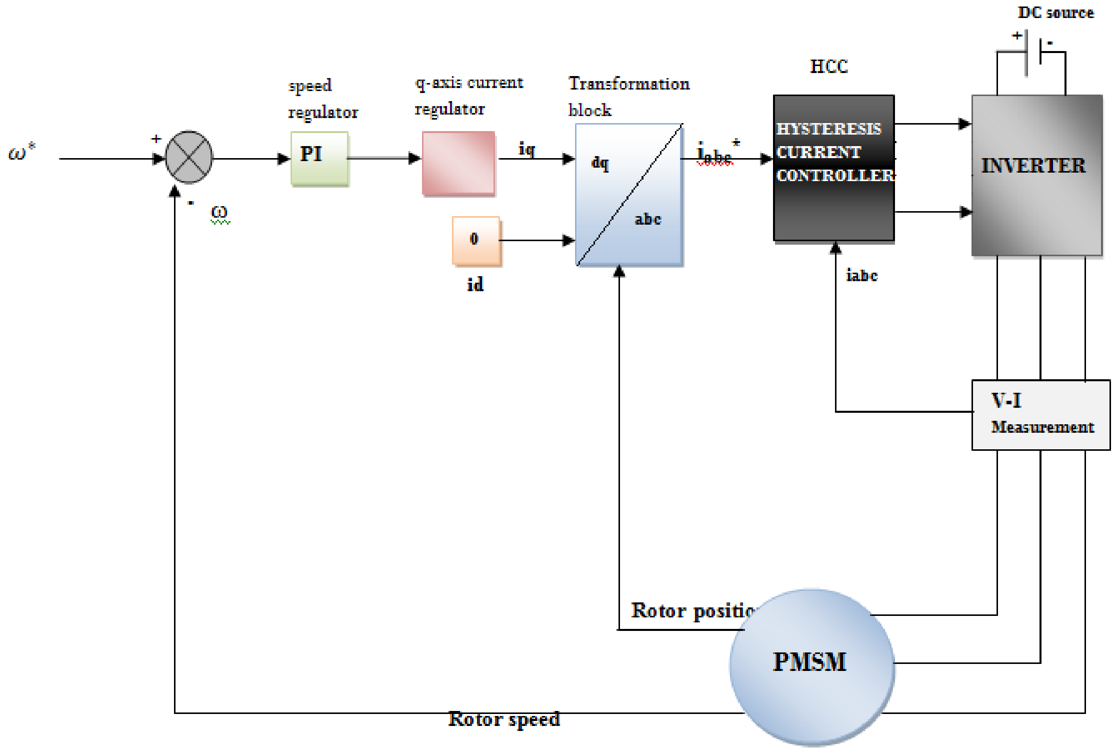


Fig. 4.7 FOC block diagram of PMSM using HCC

4.4 ROTOR FLUX ESTIMATION

The parameters that are necessary for the production of toque are mmf of stator and the rotor flux. The estimation of rotor flux is an important task for getting information about the rotor position of PMSM. In PM synchronous motor, the rotor flux is because of the magnets present in the rotor. The rotor flux in orthogonal axis (α-β) represented as:

$$\psi_{f\alpha} = \int (V_{s\alpha} - i_{s\alpha} R_s) dt - i_{s\alpha} L_s \qquad 4.25$$

$$\psi_{f\beta} = \int \left(V_{s\beta} - i_{s\beta} R_s\right) dt - i_{s\beta} L_s \qquad 4.26$$

The rotor flux can be obtained from the equation[s] (4.25) & (4.26). In the rotor flux estimation model due to presence of integrator there persist an error i.e. dc offset error in the input. So, to eliminate the error due to integrator, a high pass filter (HPF) has been modelled in series with the integrator [25]. Some phase shift is there in the rotor flux that can be seen while performing the simulation with filter and without filter. The rotor flux equation using high pass filter (HPF) given as:

$$\psi_{f\alpha}(s) = \frac{T_f(s)}{1+T_f(s)} \int (V_{s\alpha} - i_{s\alpha}R_s)dt - i_{s\alpha}L_s \qquad 4.27$$

$$\psi_{f\beta}(s) = \frac{T_f(s)}{1+T_f(s)} \int \big(V_{s\beta} - i_{s\beta}R_s\big)dt - i_{s\beta}L_s \qquad 4.28$$

As phase shift is seen, the time constant (T_f) is taken for compensation. The model for estimating rotor flux using equation^s (4.27) & (4.28) is shown in Fig.4.8. The stator current (i_a, i_b & i_c) of PMSM is transformed to α-β component and then fed to the estimated model of flux. The performance of flux is checked with and without filter.

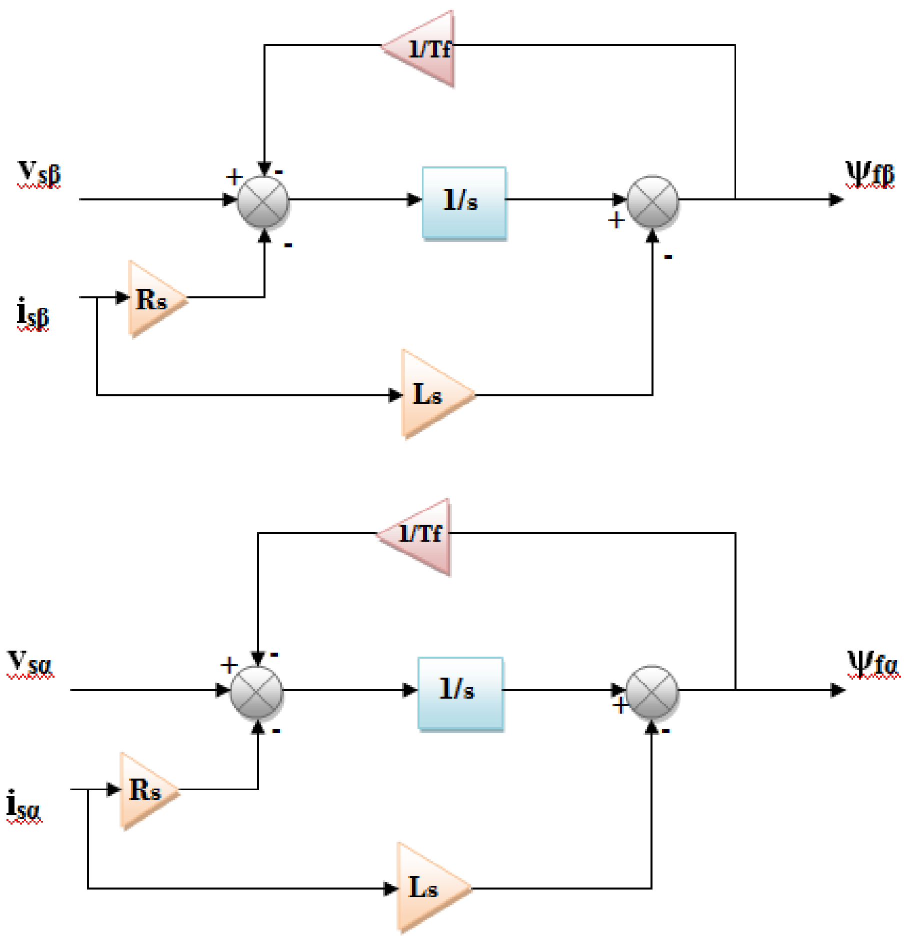


Fig. 4.8 Block diagram of estimation of rotor flux

4.4.1 PLL principle

For the implementation of rotor flux, phase locked loop (PLL) is applied to know about the position and speed of rotor of PMSM in which the $\psi_{f\alpha}$& $\psi_{f\beta}$ are taken as the input of model shown in Fig.4.9.

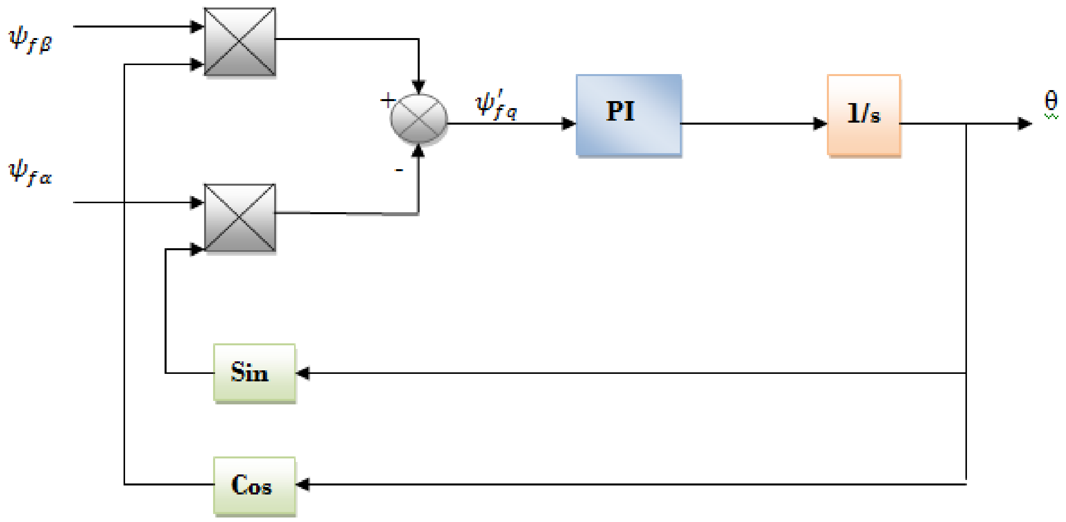


Fig.4.9 Block diagram of PLL

4.5 MODELLING & SIMULATION RESULTS

The implementation of field oriented control (FOC) using HCC & the rotor flux estimation model of PM synchronous motor is done using R2016 MATLAB/simulink. The simulink model of FOC of PMSM using HCC is shown in Fig. 4.10. The responses of PMSM is carried out at rated load. In Fig.4.11., the performance of FOC is observed at T_L =3.5Nm when the dynamic responses of speed, torque, i_q and i_s are shown.

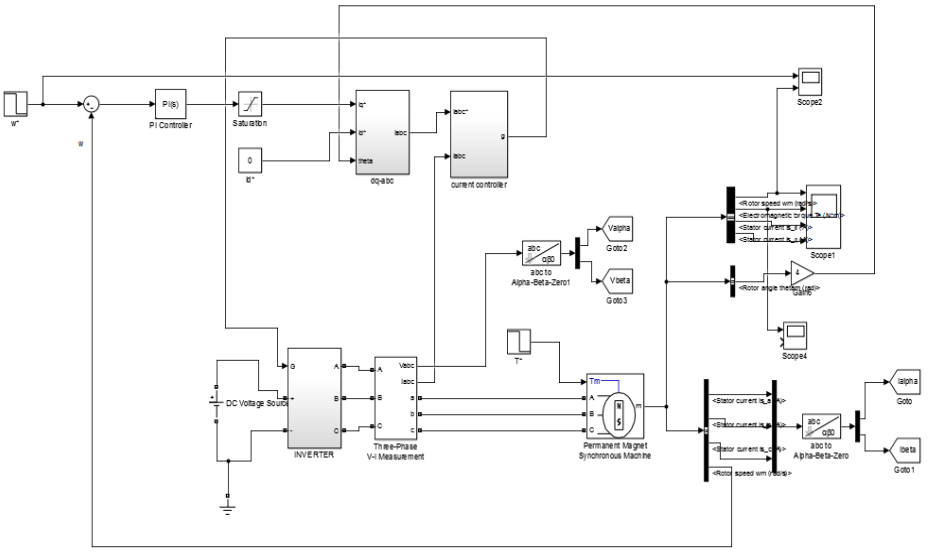


Fig.4.10 Simulink model of FOC of PMSM

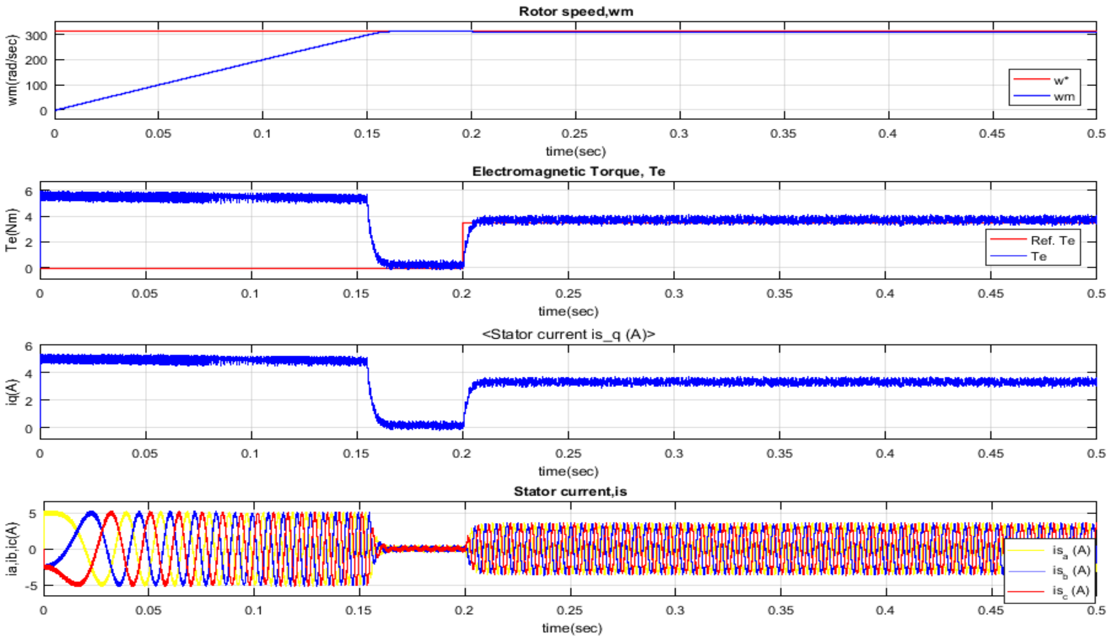


Fig. 4.11 Performance observed at rated load

As we know in electrical machine, the stator field and the rotor field are not orthogonal to each other and id is always zero. So, the only current that can be inhibited is the stator current. The response of id & stator current and the measured output voltage is shown in Fig^{s}. 4.12 & 4.13.

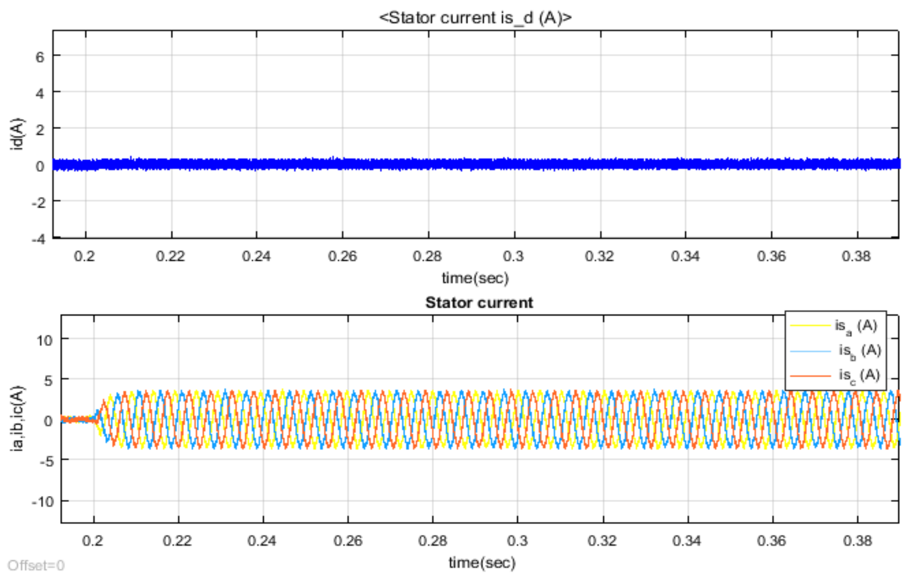


Fig. 4.12 Response of i_d & Stator currents(ia, ib & ic) of PMSM

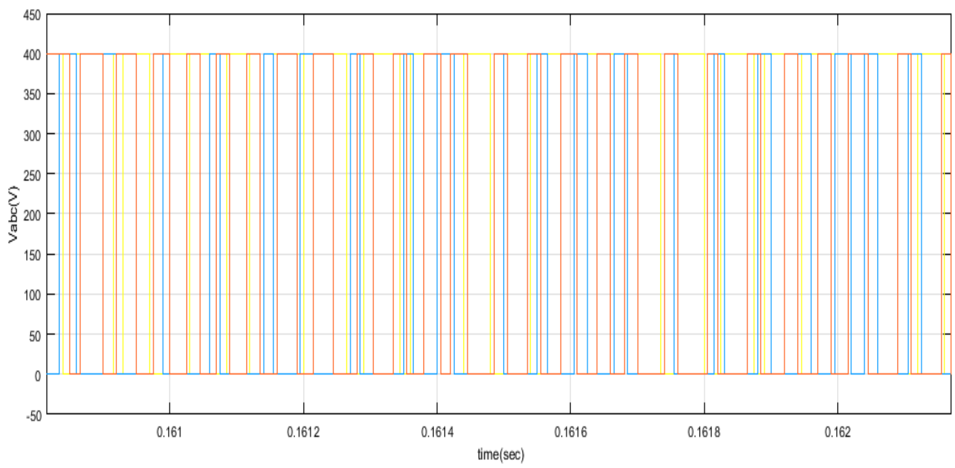


Fig. 4.13 VSI output voltage

The performance of PMSM while at different loaded condition is given in Fig.4.14 . The performance is observed when the motor started at no load with rated speed condition. At 0.2sec, a step increment in load torque is introduced (3.5Nm) followed by a step decrement in load torque at 0.5sec (1.75Nm) and finally the load torque is reduced to 0.875Nm at 0.7sec. The motor tracks the reference torque smoothly. Accordingly the stator current at these condition is shown.

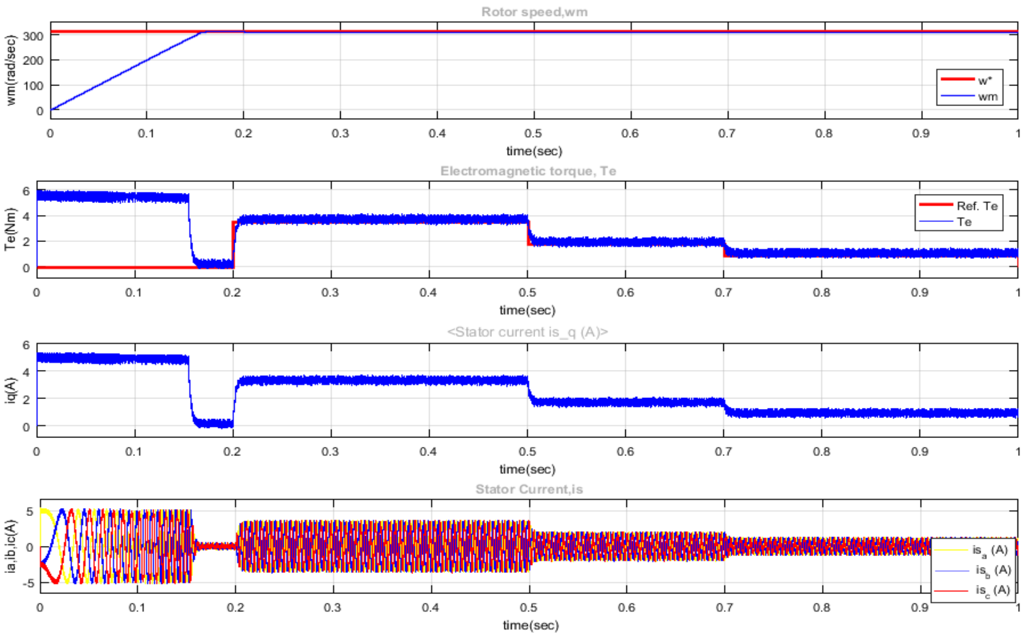


Fig. 4.14 . Performance of PMSM on different load without flux estimation

The estimation of rotor flux with filter and without filter is shown in Fig[s]. 4.15 & 4.16. A HPF has been applied in the model of flux estimation for orthogonal rotor flux, as phase shift occurred compensation was necessary and to compensate a time constant of 0.01 considered.

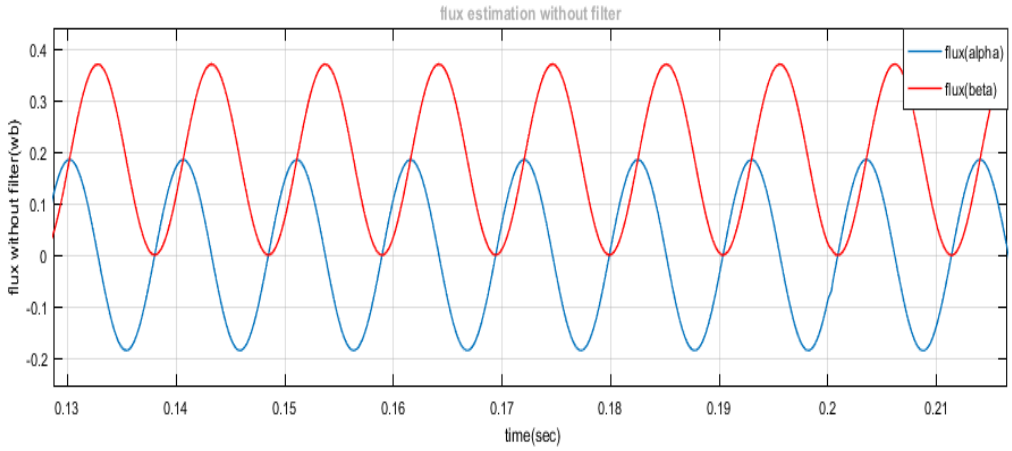


Fig. 4.15 Flux estimation without filter

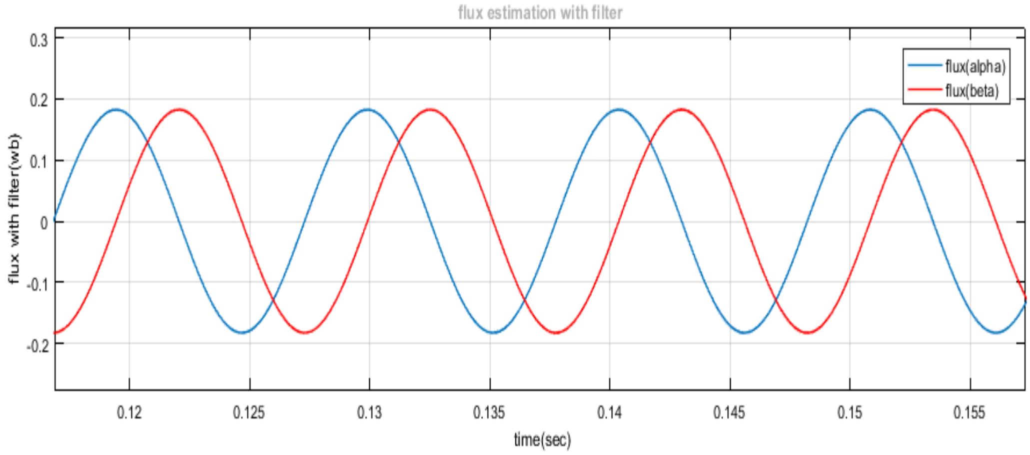


Fig. 4.16 Flux estimation with filter

The response of FOC at the rated speed 314 rad/sec with the step time of 0.5sec & at rated load condition (T_L=3.5Nm) including flux with filter in the FOC model is shown in Fig.4.17.At 0.2sec, the rotor starts to attain its speed and correspondingly the torque and stator current follows.

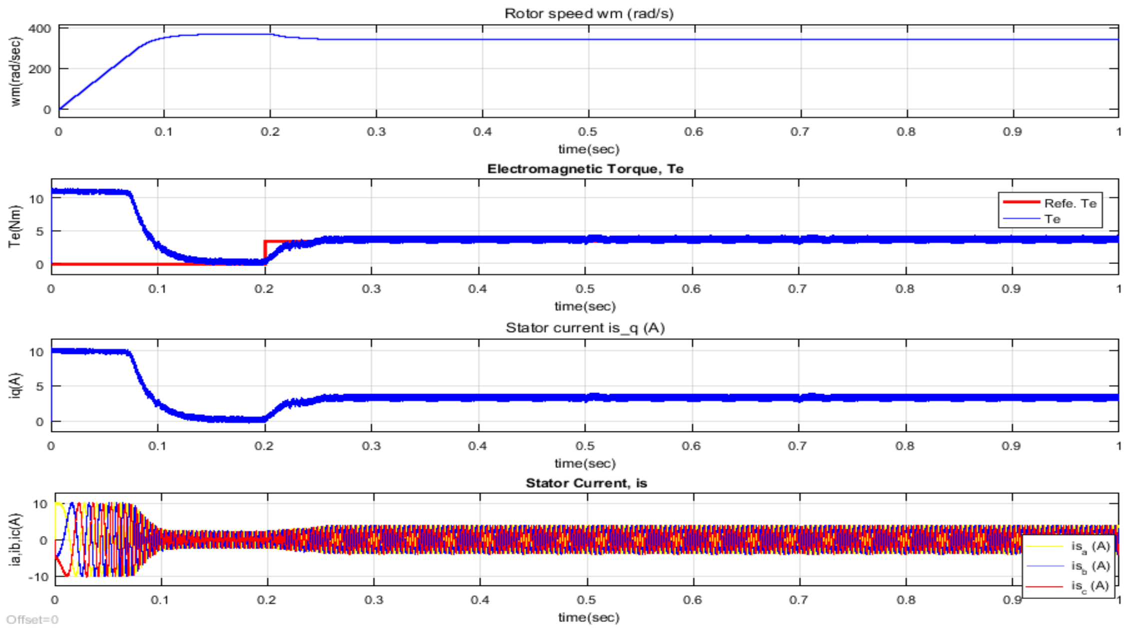


Fig. 4.17 Performance of FOC with flux estimation

4.6 CONCLUSION

The modelling of PM synchronous machine has been studied . The performance of FOC of PMSM using hysteresis current controller (HCC) at rated and different load is carried. Also the estimation of rotor flux with filter and without filter has been done. The high pass filter has been used for the elimination of error in integrator. It is observed that there is some phase shift in the rotor flux so compensation required and for that time constant of 0.01 considered. And the performance of FOC including flux estimation is observed better.

CHAPTER 5

TORQUE RIPPLE MINIMISATION

5.1 INTRODUCTION

This chapter deals with the minimisation of ripples in torque of PMSM and the controllers used for minimising ripples. It also consist of modelling and simulation results of the controller and the FOC implementation using the proposed controller.

The action between the stator current and the rotor magnetic field seems to be what causes a torque ripple to develop. The parasitic torque ripple in a PMSM causes the electromagnetic torque to periodically fluctuate, causing speed fluctuations in the steady state and affecting the motor's control precision. The different techniques shown in Fig.5.1.

The reason for ripples in torque –

- Mutual torque that is produced due to the interaction of the rotor field and stator currents.
- Reluctance torque produced due to rotor saliency.
- Cogging torque produced due to the existence of stator slots.

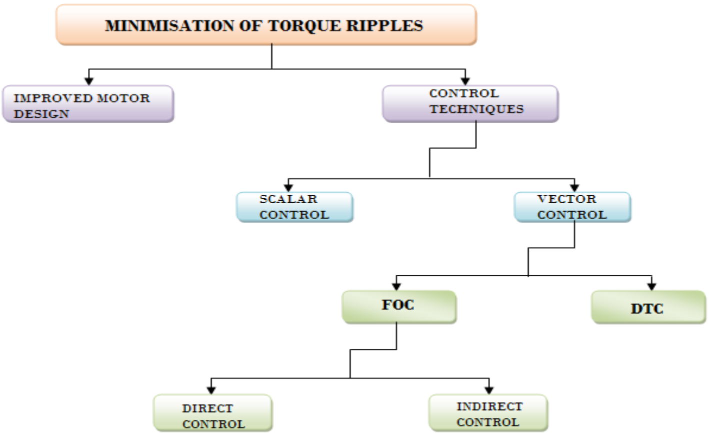


Fig.5.1 Techniques for minimisation of ripples in torque

5.2 TORQUE RIPPLE MINIMISATION

Many factors, such as cogging torque, the relationship between MMF and air gap flux harmonics, or mechanical imbalances generate torque ripple in electrical machines.

- *Torque ripple by cogging torque*

The interaction between the magnetic field of the permanent magnets and the stator slots produces variations in the reluctance depending on the rotor position, result in cogging torque in PMSM. Cogging torque is affected by factors such as slot opening width, eventual magnet width, skewing, and so on.

- *Torque ripple by interaction between the MMF and the air-gap flux harmonics*

In addition to the cogging torque, there is another component that contributes to the torque ripple under load. The action of the magneto-motive force (MMF) and the air gap flux harmonics causes torque ripple. Changes in the geometry of the machine design, particularly the number of stator slots, the number of poles, the magnet angle, and the slot opening width, can all have an impact on this component.

Basically, torque ripple is the phenomenon that can be observed in electrical drives and it can be referred as the periodic increase or decrease in o/p torque when the shaft of motor rotates. The smoothness of torque is the desirable characteristics for application of ac drives.

The position of rotor and mechanical speed of motor shown as-

$$\frac{d}{dt}(\omega_m) = \frac{1}{Jm}[T_e - T_L - B_m\omega_m] \quad 5.1$$

$$\omega_m = \frac{1}{Jm}\int[T_e - T_L - B_m\omega_m] \quad 5.2$$

$$\frac{d}{dt}(\theta_m) = \omega_m \quad 5.3$$

where, ω_m & θ_m is the mechanical rpm & position of rotor. The motor's inertia is J_m , B_m is viscous damping and T_L is the loading torque.

The viscous damping, Bm is considered to be very small so it can be ignored. Therefore, the equation (5.1) reduced to

$$T_e - T_L = J_m \frac{d}{dt} \omega_m \quad 5.4$$

if $\frac{d}{dt}$ →s, then

$$T_e - T_L = J_m \omega_m(s) \quad 5.5$$

From eq^n(5.5), the transfer function between speed of motor and torque can be written as

$$\omega_m(s) = \frac{\Delta T_m}{J_m(s)} \quad 5.6$$

&

$$\Delta T_m = T_e - T_L \quad 5.7$$

When the motor operates at low speed, there are oscillations in the speed at the corresponding harmonic frequencies as of ripple in torque, i.e. ΔT_m. So, it is important to reduce the ripples in speed that is the major cause of oscillations in speed and for that torque ripple (ΔT_m) should be minimum.

Torque ripple factor (TRF) can be defined as the percentage of difference between the maximum torque i.e. T_{max} and the minimum torque, T_{min} to the average torque and it is expressed as

$$\%\, TRF = \frac{T_{max} - T_{min}}{T_{avg}} \times 100 \quad 5.8$$

5.3 CONTROLLERS

PMSM drive performance is primarily determined by the system's accurate and direct response, as well as the control method's robustness. The PI controller is used to eliminate the steady state error. Consequently, a PI controller is extremely sensitive to lead speed changes, parameter variations, and loading conditions.

5.3.1 PI controller

The controller that is mainly used for the application of motion in control system is proportional integral (PI) controller. PI controllers compare the actual current to the reference current and generate iq and id currents, respectively. The proportional gain in it generates an output that is equivalent to the error in input and the integrator in it makes error zero in the steady state for step change in the input. The difference between the reference speed and the actual speed is calculated by the speed controller, leading in an error that is passed to the PI controller. For motion control systems, PI controllers are commonly employed. They are comprised of of a proportional gain that generates an output corresponding to the input error and an integration that keeps the steady state error for a step change in the input zero. The block diagram of the PI controller is shown in Fig.5.2.

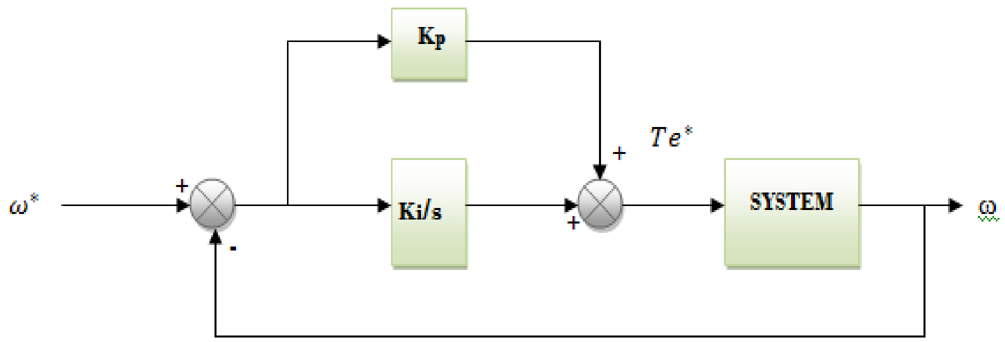


Fig.5.2 Block diagram of PI controller

Motor speed control is separated into two loops: an inner loop for current and an outer loop for speed. The order of the loops is determined by their response time, or how quickly they can be adjusted. This demands a current loop that is at least ten times as fast as the speed loop. The PMSM can be represented as a dc motor since it is operated by field oriented control. The block diagram is used to initiate the design with the innermost current loop. However, the motor in a PMSM drive system has current controllers that generate a current loop. The comparison of reference currents with actual motor currents is used for current control. The current loop is assumed to be at least 10 times faster than the speed loop, allowing the system block diagram to be reduced by assuming the current loop to be of unity gain, as illustrated in Fig. 5.3.

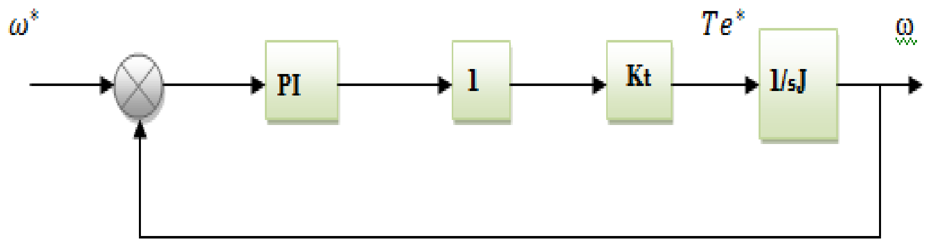


Fig.5.3 Block diagram of speed loop

5.3.2 PI-RES Controller

For three phase inverters in the stationary reference frame and the natural reference frame, a proportional resonant (PR) controller is proposed and implemented. The proportional and resonant terms are combined to form PR controller. Because PI controllers with a pole at zero frequency cannot eliminate steady state error at the fundamental frequency unless they are used in the d-q frame, such controllers have high gain around the resonant frequency and can thus eliminate steady state error when monitoring or rejecting a sinusoidal signal. The transfer function by which the effectiveness of controller can be seen is given as

$$G(s) = \frac{\omega}{s^2+\omega^2} \quad 5.9$$

The PR controller is the combined action of proportional & resonant term , this can be represented as

$$G_{PR}(s) = K_P + K_R \quad 5.10$$

where,

$$K_R = \frac{2K_{ri}\omega_c s}{s^2+2\omega_c s+\omega^2} \quad 5.11$$

where, ω is the resonance frequency. This type of controller have immense gain nearby the resonant frequency and because of this these are able to eradicate the steady state error [26]. In s-domain, P-R controller for monitoring harmonics of order h can be acknowledged. When implemented in closed loop, $G_{PR}(s)$ offers unbounded gain in open loop at the resonant frequency [27].

When the PI controller and PR controller are combined in parallel configuration, they act as PI-RES controller. The transfer function for PI & PR controller can be employed as

$$G_{PI}(s) = K_P + \frac{K_I}{s} \quad 5.12$$

& the combined PI-RES can be represented as

$$G_{PI-RES}(s) = K_P + K_I + \frac{2K_{ri}\omega_c s}{s^2+2\zeta\omega_c s+\omega^2} \quad 5.13$$

where,

K_{ri}= resonance co-efficient; ω_c= cut- off frequency & ξ = damping co-efficient

The block diagram of PI- RES controller is shown in Fig. 5.4.

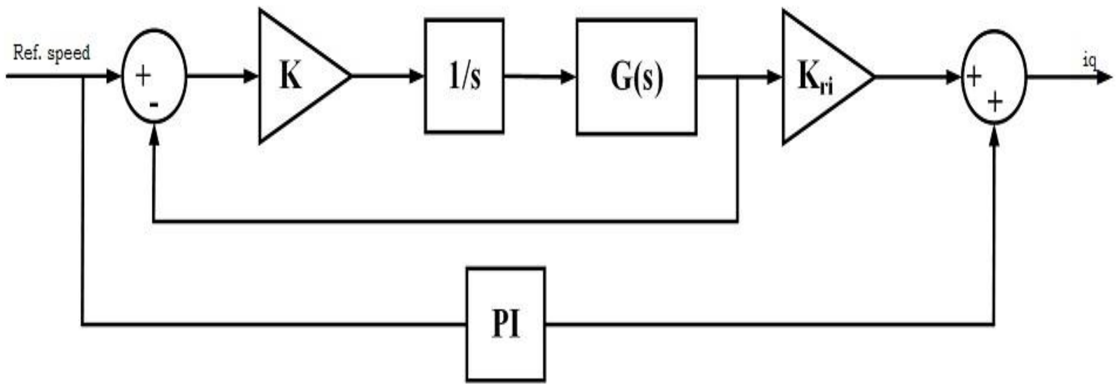


Fig. 5.4 Block diagram of PI-RES controller

5.4 MODELLING & SIMULATION RESULTS

The parameters used of PMSM used for implementation of PMSM for minimisation of ripples in torque is listed in Table 2 and the FOC simulink model of PMSM using PI-RES controller for minimisation of ripples in torque is shown in Fig. 5.5.

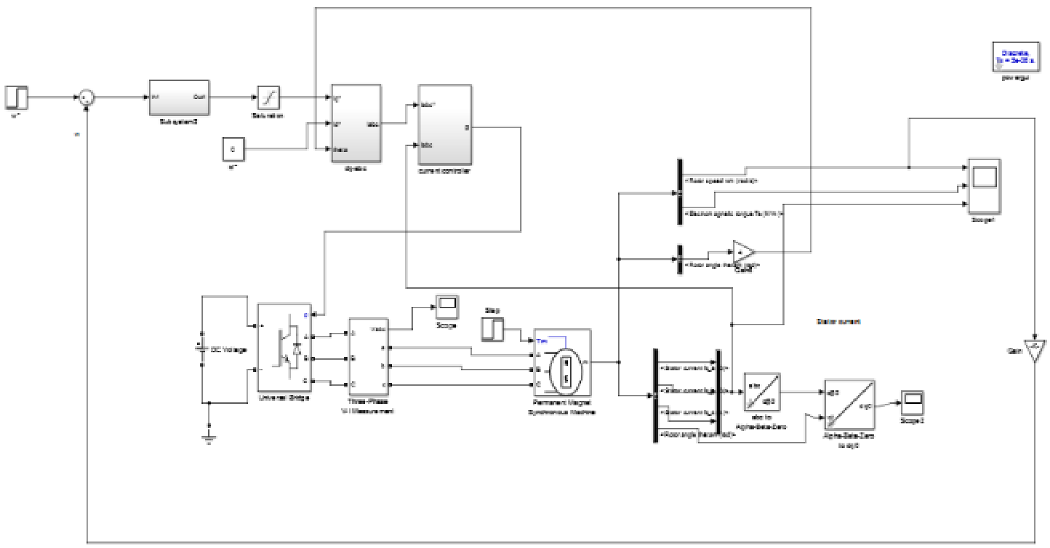


Fig.5.5 Proposed simulink model of PMSM using PI-RES controller

Table2. Specification of PMSM parameters

Rated Power, P(kW)	3.4kW
Vrated, V(v)	380V
Irated, I(A)	6.9A
Rated rpm, N(rpm)	3000rpm
Stator resistance, Rs(Ω)	1.93Ω
Flux-linkage, Ψ(Wb)	0.865Wb
No. of poles(P)	8

Inductance on quadrature-axis(L_q)	0.0114H
Inductance on direct axis(L_d)	0.0114H
Inertia of motor(J_m)	0.11kg.m^2
Rated Torque, T(Nm)	11Nm

The implementation of field oriented control (FOC) using HCC of PM synchronous motor for minimisation of ripples in torque is done using R2016 MATLAB/simulink. In Fig.5.6, the responses of PMSM is carried out at rated speed (3000rpm) and on no load(T_L=0) condition using PI controller.

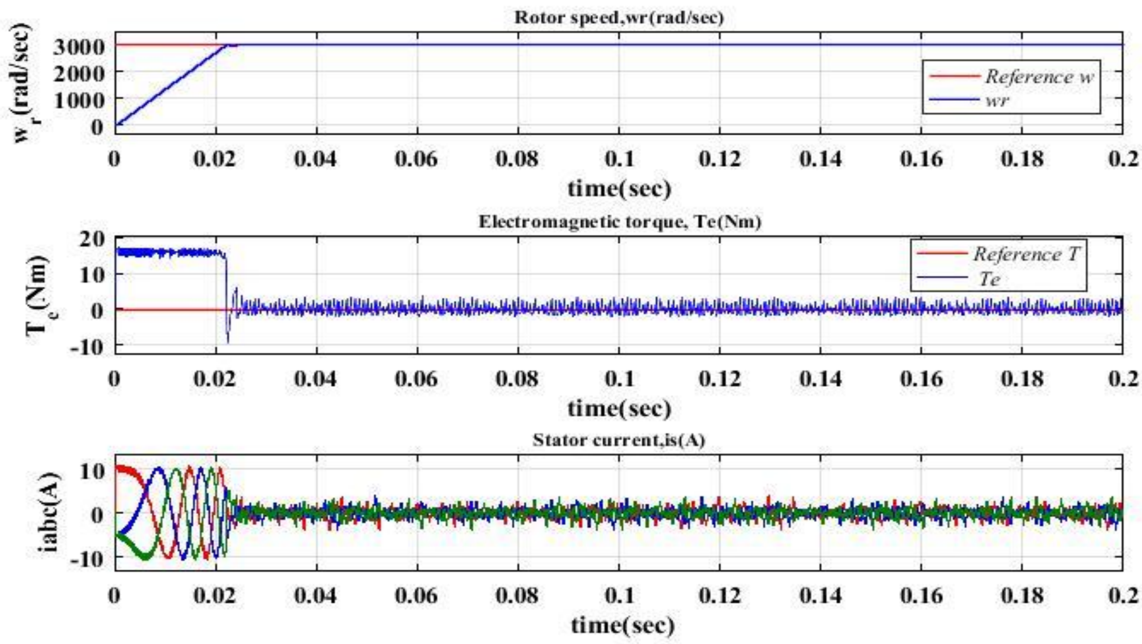


Fig.5.6 . Response of torque ripple at rated speed on No-load using PI controller

In Fig.5.7, the performance of speed, torque and stator currents using PI-RES controller is shown at the rated speed of 3000rpm on no-load condition.

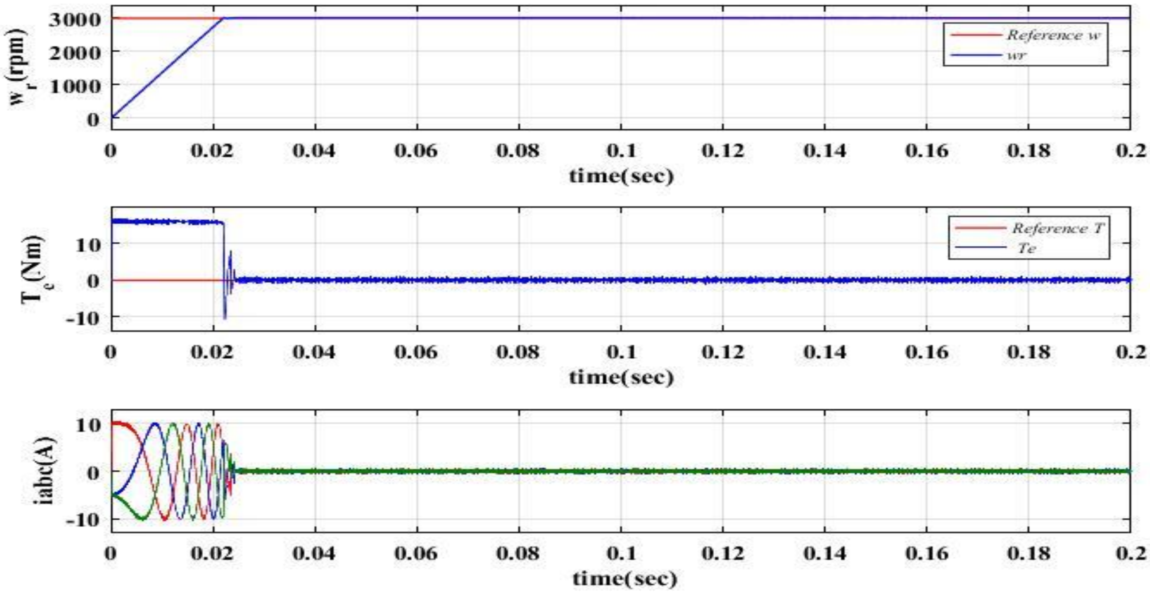


Fig.5.7 Response of torque ripple at rated speed on No-load using PI-RES controller

The response at rated condition i.e. rated load (11Nm) & rated speed (3000rpm) with the step time of 0.06sec and the ripples in torque using PI controller is observed as shown in Fig^{s}.5.8 & 5.9.

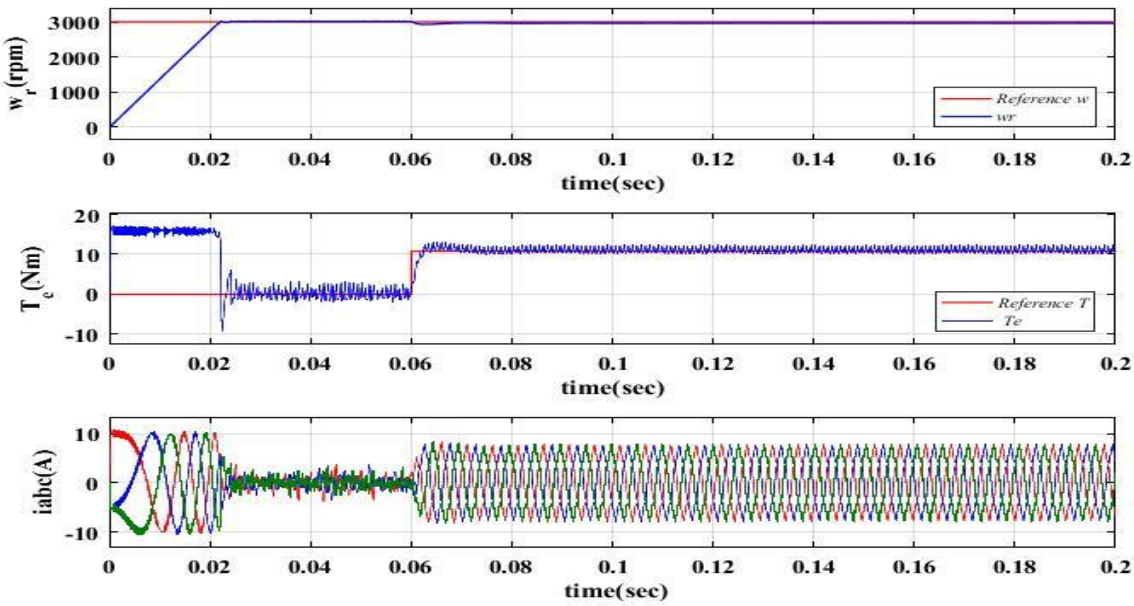


Fig.5.8 Torque ripple at rated load and rated speed using PI controller

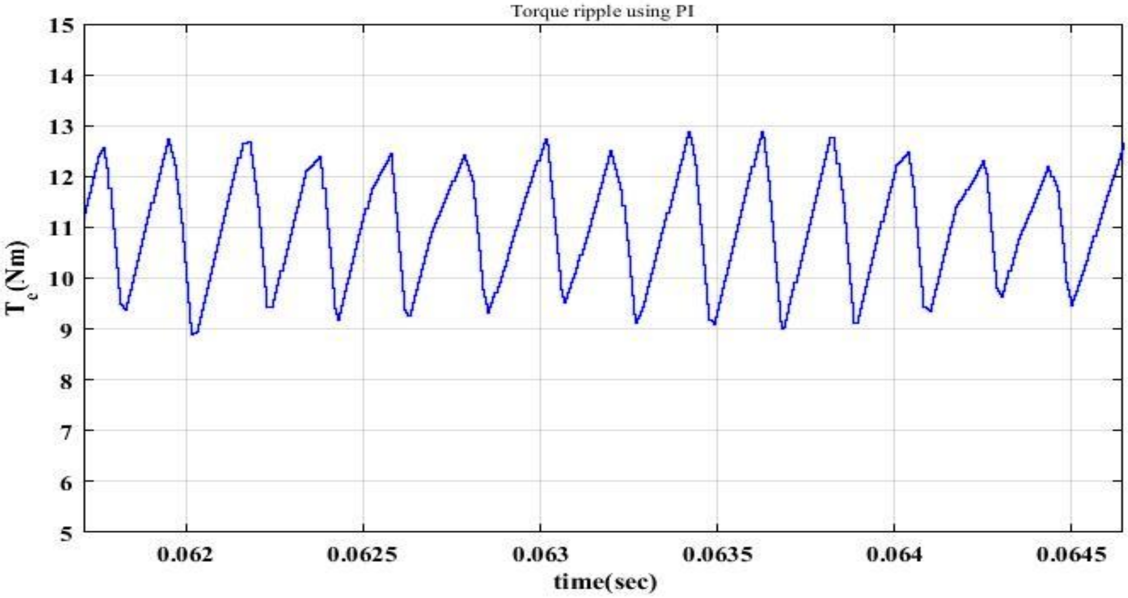


Fig.5.9 Torque ripple analysis using PI controller

The response at rated load(11Nm) condition at 3000 rpm and the ripples in torque using PI-RES controller is observed as shown in Fig[s].5.10 & 5.11.

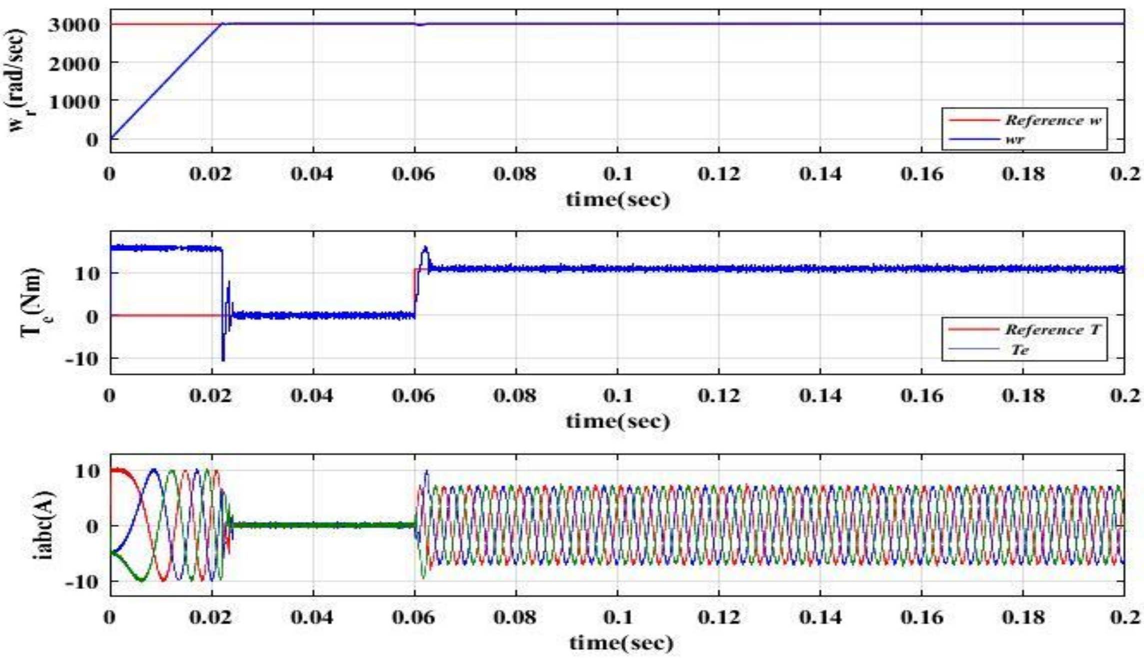


Fig.5.10 . Torque ripple at rated load and rated speed using PI-RES controller

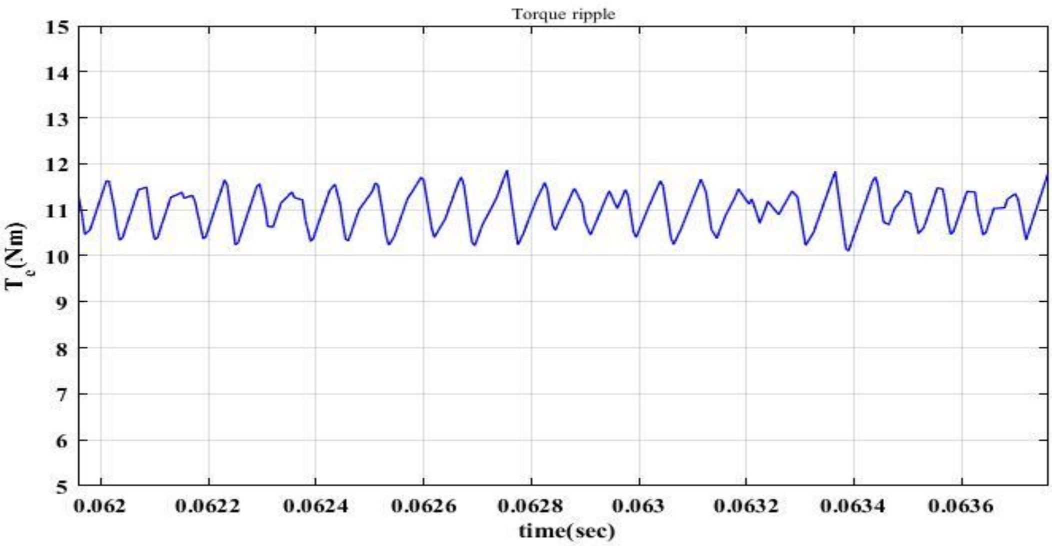


Fig.5.11 Torque ripple analysis using PI-RES controller

The dynamic performance of PMSM is compared in which the speed response, torque and current response is observed while running the motor at half load and at half of the rated speed by using PI controller and the proposed controller. It is seen in Fig^s.5.12 & 5.13 that introducing the resonant controller in parallel with PI doesn't affect the dynamic performance of drives. The motor is running effortlessly. The compared performance of torque ripple using PI and PI-RES controller is shown in Fig.5.13.

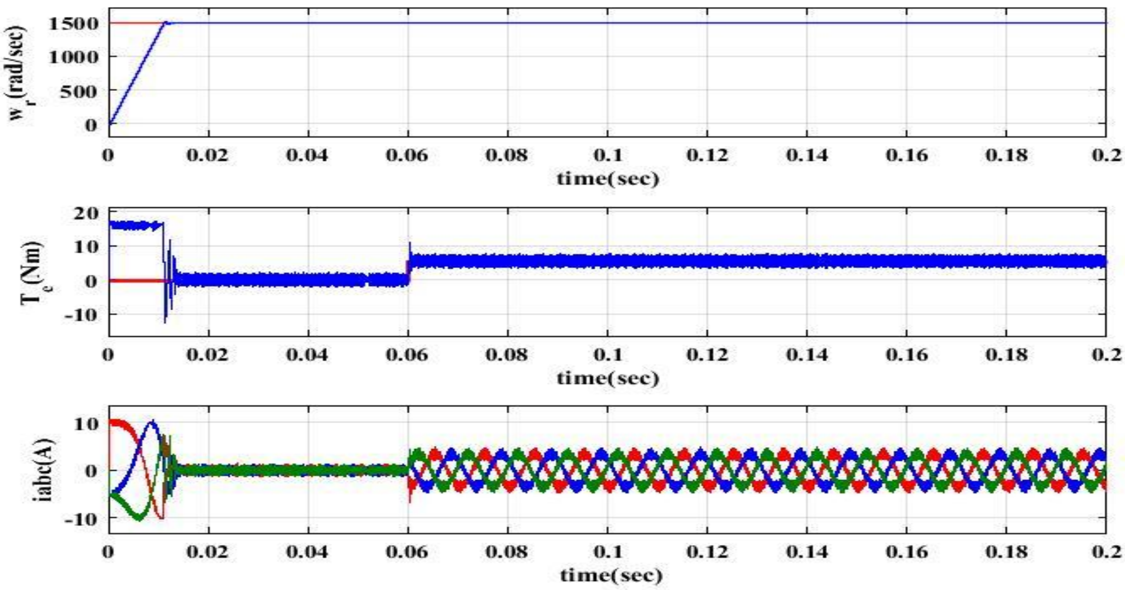


Fig.5.12 Response of PI controller at half load running at 1500rpm

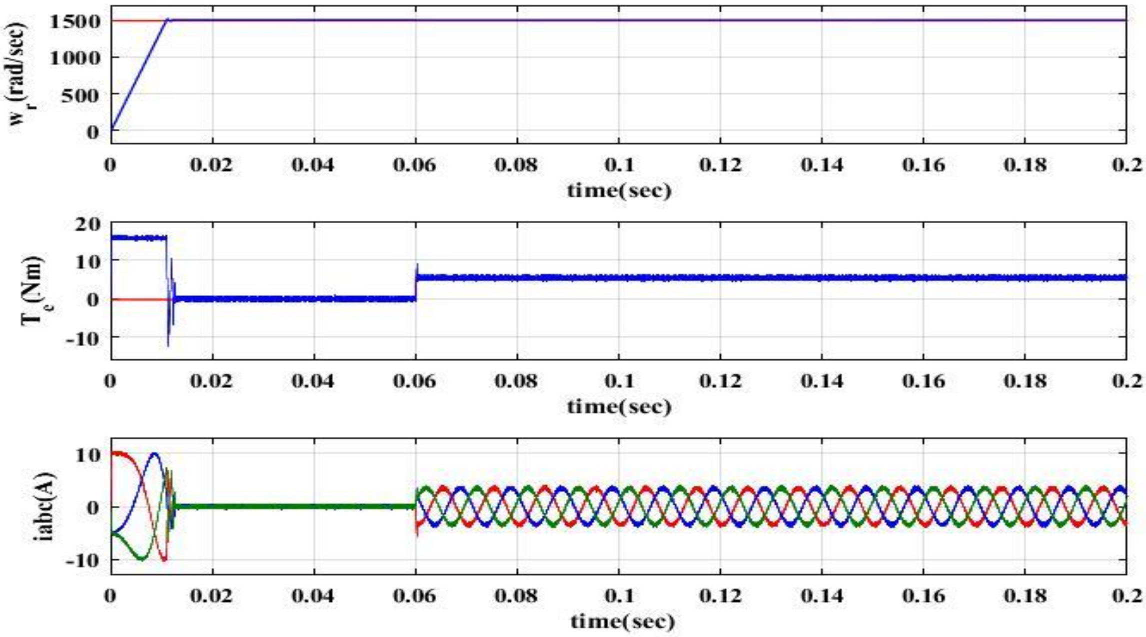


Fig.5.13 Response of PI-RES controller at half load running at 1500rpm

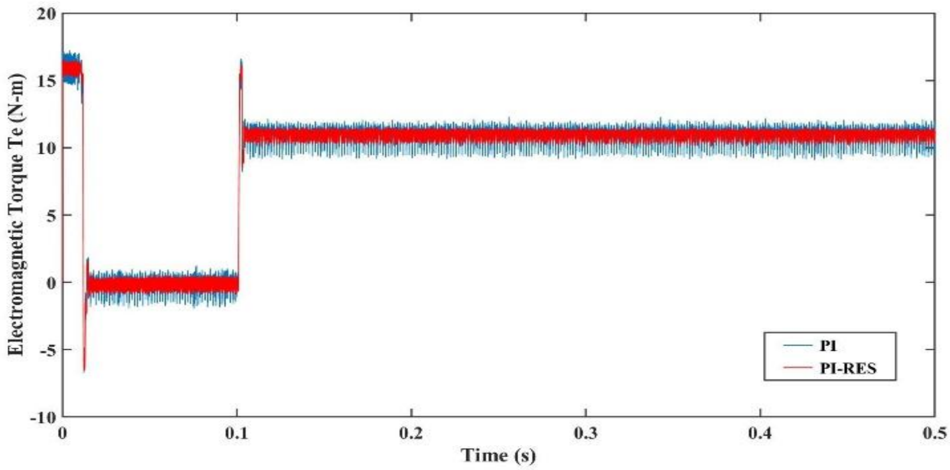


Fig.5.14 Comparison of ripples in torque using PI and PI-RES controller

The torque ripple factor calculated using expression mentioned below –

$$\%TRF = \frac{Peak\ to\ peak\ torque}{Rated\ torque} \times 100$$

Torque ripple factor (TRF) using PI controller=36.36%

& torque ripple factor (TRF) using PI-RES controller=15.45%

5.5 CONCLUSION

The performance of FOC of PMSM for the minimization of ripple in torque using hysteresis current controller at rated speed & on no-load condition and also on half load is carried. For the reduction of torque ripples, a resonant controller used in parallel with PI controller. A contrast of ripples induced in torque is also seen, with the proposed controller suppressing the ripples. The new approach, which employs the PI-RES controller, produces an improved result.

CHAPTER 6

CONCLUSION

The design of a complete Simulink model for a PMSM drive system with field oriented control is developed. Because of its flexibility in working with analog or digital devices, Simulink has been chosen from among various simulators. When compared to PSpice, the availability of several tool boxes and help in MATLAB/Simulink guides improves the modelling of large systems. Currents and voltages can be measured in each part of the system in the current simulation. The inverter is usually driven by hysteresis or PWM current controllers in such a drive system. Hysteresis current controllers have a flexible switching frequency that is defined by the hysteresis band, and if the bandwidth is too small, the device's switching capabilities may be affected. Simulating the model with a hysteresis current controller provides quicker simulations with less time and computing resources. For closed loop performance of the PMSM drive system, a speed controller has been successfully designed such that the motor runs at the desired or reference speed. The performance of FOC of PMSM is carried at different load conditions to check its dynamic performance. When implemented through rotor flux estimation the result comes better . For the minimisation of ripples induced in PMSM resonant controller is used in parallel with PI. The PI-RES controller is being used to minimise the speed torque ripple of the PMSM. When compared the traditional PI-controller based FOC technique to PI-RES controller, the simulation showed that the PI-RES controller gives better result than the PI controller.

In Future for more better result we can use Fuzzy in place of PI i.e. FUZZY RES controller and also some more implementation can be done.

REFERENCES

[1] A. Borisavljevic, E.Ho, and T. Takahashi, “Fan Drive starting into Naturally Rotating Load by Sinusoidal Sensorless Permanent Magnet Motor Control,” in Power Electronics and Motion Control Conference,2006,pp.1190-1198.

[2] T. Sebastian, G. Slemon, and M.Rahman, “ Modelling of permanent magnet synchronous motors,” *Magnetics, IEEE Transactions* on, vol.22, pp. 1069-1071,1986.

[3] T. M. Jahns, G. B.Kliman, and T.W. Neumann, “Interior Permanent magnet Synchronous Motors for Adjustable Speed Drives,” *Industrial Applications, IEEE Transactions on*, vol.IA-22, pp. 738-746,1986.

[4] P. Pillay and R. Krishnan, “Modelling of permanent magnet motor drives,” *Industrial Electronics, IEEE Transactions on*,vol.35, pp. 537-541, 1988.

[5] P. Pillay and R. Krishnan , “Modelling, Simulation, and analysis of permanent magnet motor drives. I. The permanent magnet synchronous motor drive,” *Industry Applications, IEEE Transactions on*, vol.25, pp. 265-273,1989.

[6] B. K. Bose, *Modern power electronics and AC drives*: Prentice Hall, 2002.

[7] G. Venkaterama, “Simulink Permanent Magnet Simulation,” *University of Wisconsin.*

[8] Matlab-Works-Support, “ PM Synchronous Motor,” *http://www.mathworks.com*

[9] S. Morimoto, Y. Tong, Y. Takeda, and T. Hirasa, “ Loss minimization control of permanent magnet synchronous motor drives, “ *Industrial Electronics, IEEE Transactions on*, vol. 41, pp.511-517, 1994.

[10] J Hu, and Bin Wu, “ New Integration Algorithm For Estimating Motor Flux over a Wide Speed Range,” *IEEE Trans. Power Electron.*, vol.13, No.5, pp. 969-977, 1998.

[11] M.S. Islam, R. Islam and T. Sebastian, " Experimental verification of techniques of permanent magnet synchronous motors for low- torque –ripple applications", *IEEE Transactions on Industry Applications*, vol. 47, no.1, pp. 88-95, 2011.

[12] Identification and compensation of Torque ripples of PMSM in a Haptic context Z. Jabhour, G. Champions.

[13] Sliding-Mode control of Permanent Magnet synchronous motor with Uncertainty Estimation Markus Reichhartinger and Martin Horn. *International Journal of Mechanical and Materials Engineering 1:2* 2010.

[14] Torque ripple minimization , suppress harmonics, and noise of brushless pm synchronous motors derived by field oriented control Hamdy Mohamed Soliman, and S. M. Hakim. IJRRAS, September 2012, vol.12, Issue 3.

[15] Simple Method of Torque Ripple Minimization and performance Characteristics Enhancement of Fuel cell based PMSM Drives. International Journal of Computer Applications (0975- 8887) vol.19, No.2, April 2011.

[16] Torque Ripple Reduction in a PMSM driven by Direct Torque Control . L. Romeral, A. Fabrega, J. Cusido, A. Garcia, J.A. Ortega IEEE Transactions 2008.

[17] Torque Ripple Minimization in PM Synchronous Motors Using Tooth Shape Optimization Ali Jabbari Majlesi Journal of Mechanical Engineering, vol. 3, No. 2-2010.

[18] P. Mattavelli, L. Tubiana and M. Zigliotto, " Torque ripple reduction in PM synchronous motor drives using repetitive current control", IEEE Trans. Power Electron., vol.20, no. 6, pp. 1423-1431, Nov. 2005.

[19] Weizhe Qian, S.K. Panda, and Jian-Xin xu, "Torque ripple minimization in PM

synchronous motor using iterative learning control", IEEE Transactions on Power Electronics, vol. 19, no. 2, pp. 272-279, March 2004.

[20] R. Krishnan, Electric Motor Drives Modelling, Analysis and Control Pearson Education, 2001.

[21] B.K. Bose, Power Electronics and variable Frequency Drives, 1 ed: Wiley, John & Sons, 1996.

[22] A. Tripathi and P. C. Sen, "Comparative analysis of fixed and sinusoidal band hysteresis current controllers for voltage source inverters", *IEEE Transactions on Industrial Electronics*, vol.39, no.1, pp.63-73, Feb 1992.

[23] S Suryakant, M. Sreejeth and M. Singh, "Performance Analysis of PMSM Drive using Hysteresis Current Controller and PWM Current Controller", 2018 IEEE International Students' Conference on Electrical, Electronics and Computer Science (SCEECS), Bhopal, India,2018, pp.1-5.

[24] S Suryakant, M. Sreejeth and M. Singh, "Sensorless control of PMSM Drive with BEMF based MRAC Algorithm", 2019 International Symposium on advanced electrical and communication technologies (ISAECT), Rome, Italy, 2019, pp.1-6.

[25] Rui Gao, Iqbal Husain, and Jianyong Su, " An improved Rotor Flux Estimation Strategy for Position Sensorless Control of Surface mount permanent magnet synchronous motor", IECON2014, pp.404-409, 2014.

[26] Gao, J., Wu, X, Huang, S., Zhang, W., & Xiao, L. (2017). "Torque ripple minimization of permanent magnet synchronous motor using a new proportional resonant controller", IET Power Electronics, 10(2), 208-214.

[27] Yepes, A.G., Freijedo, F.D., Lopez, O., et al.: ' High performance digital resonant controllers implemented with two integrators', IEEE Trans. Power Electron, 2011, 26,(2), pp. 563-576.

LIST OF PUBLICATIONS

1. Shilpa Ranjan and Mini Sreejeth, “Field Oriented Control of PMSM through Rotor Flux Estimation Using two-level Hysteresis Current Controller”, *The IEEE International Conference on Intelligent Technologies(CONIT 2021),* Hubballi, Karnataka, India.
2. Shilpa Ranjan and Mini Sreejeth, “ MINIMISATION OF RIPPLES IN TORQUE OF HYSTERESIS CURRENT CONTROLLED PMSM USING PI-RES CONTROLLER”, *IEEE 2nd International Conference of Emerging Technologies 2021*, Belgaum , Karnataka ,India.